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FRACTURE TOUGHNESS OF
SUBMERGED ARC WELDED
HY - 80 STEEL

by

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HY-80 STEEL

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BRYAN P. WILSON

Submitted to the Departments of Material Science and Engineering and Ocean Engineering on May 7, 1982 in partial fulfillment of the requirements for the degrees of Master of Science and Ocean Engineer.

ABSTRACT

The welding parameters; voltage, current and travel speed, have been examined to determine the optimum values for two commercial fluxes. The two fluxes; Lincoln 880, and Oerlikon OP121TT were also tested to determine the reasons for a reported difference in toughness, even though the flux compositions were nearly identical.

The welding parameters were varied in a statistically designed experimental program. Weld metal toughness was measured by the Charpy"V" notch test at a temperature of -50 degrees C. The weld metal chemistry was measured near the notch of the Charpy specimen and the type of non-metallic inclusions was determined by X-ray fluorescence. The results show that both fluxes are able to produce Charpy energy values of above 80 Joules when the correct values of voltage, current and travel speed are used. The standard deviation of Charpy energies for the welds made with OP121TT was less than that of the welds made with Lincoln 880. The mean value of Charpy energy of both fluxes was practically identical at 84 Joules.

Inclusions in the weld metal were found to consist primarily of silicon, aluminum, manganese and calcium. Aluminum and calcium are found primarily in the fluxes, while silicon and manganese are in the flux, the electrode and the baseplate. The number and distribution of inclusions did not appear to alter the toughness.

Chemical analysis of the fluxes revealed minor chemical differences. The OP121TT contained 2 % MnO, and produced weld metal 0.2 % richer in Mn than did the Lincoln 880. Sodium was detected in the Lincoln 880 but not in the OP121TT. Potassium was not found in the Lincoln 880 but was discovered in the OP121TT. These slight differences could be the cause of the performance variations between the two fluxes.

Significant differences were found in the toughness due to variations in the welding parameters. Most influential were current and travel speed. No direct correlation was found between heat input and fracture toughness, however optimum toughness was attained at a heat input of 2.3 KJ/mm for both fluxes.

The loss of Mn was found to depend on welding current when using the Lincoln 880 flux. The loss occurs because this flux lacks MnO which prevented the loss of Mn when welding with OP121TT. The degree of loss in the case of Lincoln 880 is at least partially explained by the variations in arc length caused by the welding parameters.

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LIST OF SYMBOLS

V	Welding Voltage
I	Welding Current
T	Travel Speed of Welding Head
D	Electrode Diameter
A	Electrode Cross Sectional Area
L	Electrode Extension
J	Joules
Cv	Charpy Fracture Energy
R	Coefficient of Determination for Regression (Given as R Squared)

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The Electic Boat Division of General Dynamics supplied the material and performed much of the testing. The assistance of Niel Fitchelberg of Electric Boat was invaluable in the analysis of the data.

I must also express my thanks to the United States Navy for providing the opportunity to study at The Massachusetts Institute of Technolgy.

1. INTRODUCTION

1.1 OVERVIEW

Submerged arc welding has become an important method of joining. It offers the benefits of rapid deposition combined with automatic or semiautomatic control. Since its introduction in the 1930's improvements in the fluxes and electrodes have resulted in higher quality deposits. The "quality" can be measured in many ways, but one important factor is fracture toughness. Toughness becomes more important as material strength increases because higher strength material is less tolerant of large flaws. The construction of pressure vessels, submarines, and structural members from high strength steels places significant emphasis on notch toughness. For this reason much effort has been expended on developing tests to measure toughness and to control weld metal chemistry. Microstructure control has dominated the research, often focusing on additions of alloying elements to the base plate, electrode or flux. Although the chemical composition of the weld is important, of equal concern is the thermal cycle of the welding process. Heating of the base plate adjacent to the weld may cause deterioration in the mechanical properties of the joint. It is the cooling rate and the weld metal composition which determine the microstructure and properties of the weld.

1.2 WELDING VARIABLES

There are many factors to consider when attempting to control the properties of the welded joint. It is perhaps worthwhile to list some of the most important variables involved in submerged arc welding.

1. Base plate
   - a. composition
   - b. original microstructure
2. Flux
   - a. composition
   - b. form
     - 1.fused
     - 2.agglomerated
     - 3.bonded
     - 4.particle size
3. Electrode
   - a. composition
   - b. diameter
4. Welding conditions
   - a. voltage
   - b. current
   - c. weld travel speed
   - d. preheat/interpass temperatures
   - e. number of passes
   - f. electrode stickout or extension
   - g. electrode feed rate
   - h. number of electrodes
   - i. joint geometry/preparation
   - j. assembly restraint

There are a number of less significant variables which are not included in this list. Unfortunately the interactions and interrelations of these variables are not well known. Many of the variables are interdependent and the control of any one can be a major undertaking. For example, the actual composition of any two heats of steel can vary markedly from the aim analysis. Steel plate is ordered to meet specifications which reflect the trade off between compositional control and the cost of obtaining that control.

The choice of welding consumables and specific welding parameters is critical to the production of high quality welds. The choices are many and the factors are interrelated in ways which are not fully understood. Selection of consumables and welding parameters usually begins with trial and error testing. Experience with a given welding process makes this testing easier, but the variables are so numerous that it is often difficult to determine valid trends.

The study presented here has focused on a systematic variation of what are commonly considered key parameters in submerged arc welding, namely: voltage, current and travel speed. The resulting weld toughness is the variable that is to be optimized. Learning how the variables influence toughness is the immediate goal, but developing a framework for further study of the fundamental factors controlling submerged arc weld

fracture toughness is a more general concern. In addition, two fluxes of nearly identical composition have been reported to produce different toughness welds [1]. An explanation for this behavior is sought.

1.2.1 Base Plate

The chemical composition of HY-80 made to military specification [2] is shown in table 1. Considerable experience has been obtained with this material and the chemistry limits imposed are the first step in the control of the physical properties. HY-80 is a quenched and tempered steel which achieves consistant properties in heavy sections through extensive alloying. A brief description of the role of these alloying elements is given below.

The carbon content is adjusted to insure good hardenability and at the same time good weldability. Too much carbon will impair weldability. Manganese is added to improve the hardenability and to reduce problems associated with sulfur. The phosphorous and sulfur content are required to be low because these elements can reduce toughness and cause hot tearing. Silicon is added to control oxygen content. Molybdenum helps to minimize susceptibility to temper embrittlement while also increasing hardenability. Nickel improves toughnesss and chromium increases strength and corrosion resistance.

TABLE 1
LIMITS OF LADLE and CHECK CHEMISTRY FOR HY-80

	WT PERCENT LADLE	WT PERCENT CHECK
CARBON	.12-.18	.10-.20
MANGANESE	.10-.40	.10-.45
PHOSPHORUS	.025 max	SAME AS LADLE
SULFUR	.025 max	SAME AS LADLE
SILICON	.15-.35	.12-.38
NICKEL	2.00-3.25	1.93-3.32
CHROMIUM	1.00-1.80	0.94-1.86
MOLYBDENUM	.20-.60	0.17-0.63
TITANIUM	.02 max	
VANADIUM	.03 max	
COPPER	.25 max	

Note S + P must be less than .040 wt percent in both the ladle and check analyses

(Taken from MIL-S-16216H)

TABLE 2 BASE PLATE AND ELECTRODE CHEMISTRY

	C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	Ti
AX-90 ELECTRODE	.050	.46	1.31	.016	.007	.066	1.93	.41	.058	.003	.013
HY-80 PLATE	.16	.22	0.26	.012	.011	1.35	2.17	.23	.004	.011	.002

(Analysis by emission spectroscopy)

The heat treatment of the rolled plate begins with water quenching from 840-900 C (1550-1650 F). Tempering is performed between 620 and 680 C (1150-1250 F) followed by a second quenching in water. Investigators from the Welding Institute [3] have found problems with banding in HY-80 which is attributed to segregation of the elements manganese, molybdenum, chromium and nickel during ingot solidification. Banding will make control of the amount of martensite difficult and will cause variation in the physical properties.

The composition of the base plate will influence the weld metal composition due to dilution of the electrode and the parent plate in the weld pool. This produces a complex situation from which it is difficult to predict the resulting joint properties based on the welding parameters and starting chemistry alone. It is for this reason that most optimization finds its basis in trial and error testing.

1.2.2 Flux

Welding fluxes are complex mixtures of minerals formulated to impart various properties to the weld metal and the fused slag. Jackson [4] has provided a concise review of welding fluxes in general. Various forms of submerged arc fluxes are available and offer distinct advantages. The basic forms are i) fused ii) agglomerated and iii) bonded fluxes. The fused fluxes are made by melting the minerals and fracturing the

fused solid to the required particle size.

This type of flux is very uniform chemically. In addition it is generally nonhygroscopic and is suitable for high welding speeds.

Bonded and agglomerated fluxes are similar in that the required minerals are held together with a binding agent, usually sodium or potassium silicates. The advantage of this type of flux is in energy costs of manufacture, although historically they were developed to avoid infringing the patents of fused fluxes. Metallic deoxidizers and ferroalloy additions can be made because of the relatively low temperatures used in drying and setting the binder. This type of flux tends to produce more gas during welding and is likely to be nonhomogeneous. The oxides of sodium and potassium also serve to improve arc stability because of their relatively low work functions.

Flux composition is adjusted to provide a stable environment for the welding arc and to maintain or alter the chemical composition of the weld metal. Additions of MnO, for example, can increase the Mn content of the deposit and are known to help the formation of acicular ferrite, the microstructure most favorable to high toughness [5,6]. The viscosity of the slag is reduced by addition of CaF_2. This is important since it will determine how well the molten slag covers the weld pool.

The percentage of small particles is usually increased when high current is desired.

1.2.3 Filler electrode

In addition to the flux, the electrode provides another important way to control the weld metal chemistry. Electrodes used in welding HY-80 contain relatively high amounts of Mn, and Ni (1.3% and 2.0% respectively) because investigations have shown these elements to control the growth of ferrite at the austenite grain boundries [6,7].

The diameter of the electrode is important because it will determine the maximum current for a given voltage. Larger diameter electrodes will allow more rapid deposition.

1.2.4 Welding conditions

In submerged arc welding as well as any process that uses the arc as a heat source, the current and voltage will be influential in determining the energy transferred to the joint. The travel speed and the power in the arc determine the heat input which will pass to the joint. The initial plate temperature (pre-heat) and the thermal conductivity of the materials involved (including the flux) are the additional variables that control the temperature cycle experienced. The temperatures and cooling rate as well as the metal chemistry will determine the microstructures. The welded joint cannot be considered to be homogeneous in any of the variables mentioned. Compositional and thermal gradients are significant

[5,8,9]. The number of passes is also an important factor in the heating and cooling cycle as well as the chemistry of the weld metal. More passes in a given joint will mean that a greater proportion of the weld metal will be affected by heating and cooling. The microstructure of the weld will be changed after each pass. The grain size in the heat affected zone, which must include the previously deposited beads, will increase. Depending on the temperature and location in the metal, segregation of certain elements will occur. The inclusion size and distribution will also be altered.

Changes in electrode stickout will cause variations in the temperature along the electrode as it moves into the arc zone and melts. The longer the electrode protruding from the welding head, the greater the electrode preheat due to resistance heating [10].

Welding current can be controlled by adjusting the electrode feed rate. The amount of electrode melted in a given time is proportional to the feed rate. An increase in feed rate will result in an increase in the proportion of the voltage drop along the electrode. For this reason the length of the arc should decrease if the feed rate is increased. If the arc length is reduced, then the time metal drops spend in the plasma will also be reduced. If Mn, for example, is lost while the drops are in the plasma, a shorter arc will allow less Mn to

transfer into the slag. Longer arc lengths will provide more time for such a reaction to occur.

One important reason for employing submerged arc welding is the rapid deposition rate. A further increase in deposition rate can be obtained if more than one electrode is used [11,12]. There are many ways to employ multiple electrodes but the control problem is clearly more complicated. The magnetic forces around the arc will cause an interaction that may be difficult to control. With two or more electrodes, the amount of heat that can be transferred is also potentially greater and the heat affected zone may be larger.

The type of joint employed will also affect the end result. The amount of filler material needed and therefore the number of passes will vary with joint design. As the joint cools after each pass, the shrinkage of the metal will induce stresses that will either distort the assembly or result in yielding [13]. The method one uses to locate and hold the assembly during welding must also play a role in the residual stress remaining upon completion. The resulting joint integrity can be greatly influenced by the location and the magnitude of the residual stresses especially when defects are present. HY-80 has been observed to crack many hours after welding due to embrittlement caused by hydrogen [14]. Residual stresses will always be present in welded structures and should be accounted for in design.

2. PREVIOUS WORK

The quality of welded structures has seen remarkable improvement in the last 10 to 15 years. Much of the progress has been due to the recognition of the relative importance of the welding parameters. The term "welding parameters" is rather broad as it can refer to almost anything one cares to control. The list of variables given earlier represents a sample of some of the parameters that have been varied in previous welding investigations.

2.1 METAL TRANSFER IN ARC WELDING

The form of metal transfer in a welding arc with inert gas shielding has been studied by Lesnewich, Gilette and Breymeir and others [10,15]. Three distinct forms of metal transfer have been observed. These are: globular, spray and short-circuit transfer. The most important factor in determining the type of transfer is the current. For low current levels transfer is globular, changing to a progressively finer stream of drops as current increases. The transfer form will eventually change to a spray at very high currents. The polarity of the electrode determines the current level at which the transfer form will change. While the investigations cited were conducted with steel electrodes with argon shielding, one would expect the same transfer modes to exist in the plasma of a submerged arc, although the current densities employed

in submerged arc welding usually result in spray transfer. Short circuit transfer normally occurs only when the arc is started. Lesnewich [10] developed an equation that expresses the transition current (the current at which the form of transfer changes to a spray).

$$Is = 60 + 3400\ D - 30\ L$$

Where D is the electrode diameter in inches

and L is the stickout length or extension in inches.

Another equation given by Lesnewich relates the minimum current required for a rotating spray which occurs at a higher current.

$$Ir = 25 + 1350\ D + 14.5\text{x}10^{4}\ D^{2}/L$$

For an electrode of 3/32 inches and a stickout of 3/4 inches

$Is = 356$ amps

$Ir = 2737$ amps

It is not clear that the above equations apply to submerged arc welding because it is difficult to observe the metal transfer underneath the flux. Some investigators have used X-Ray techniques to observe the process [16,17]. Wilson and Jackson [16] have observed that the shortest distance between the electrode and the weld metal grows linearly with voltage but will vary with the flux used. The arc length was also observed to decrease with increasing travel speed [19]. Most of the melting is due to arc (anode heating in the case of reverse polarity).

The remaining melting is caused by resistance heating of the electrode as it emerges from the contact tip.

Wilson, et al. [18] studied the effects of welding parameters on electrode melting rate in the submerged arc process. Using their data one can express the melting rate M (lbs/min) of the electrode due to all forms of heating in terms of the current I (amps), the electrode diameter D (inches) and the electrode extension L (inches);

$$M = I/1000\ [0.35 + D^2 + 2.08\times10^{-7}\ (I\times L/D^2)^{1.22}]$$

for $I = 500$ amps

$D = 3/32$ inches

$L = .75$ inches

$M = .226$ lbs/min $= 13.5$ lbs/hr $= 117$ in/min

Another formula was developed by Lesnewich [10] for the GMA process using reverse polarity with argon shielding and 1% oxygen.

$$M = (0.017 + 0.37\ A)\ I + 3.69\times10^{-8}\ L\ I^2/A^{1.26}$$

where A = cross sectional area of the electrode

and for the same values used above

$M = 13.43$ lbs/hr or 117 in/min of 3/32 inch electrode

Both of the equations give identical and reasonable electrode feed rates based on the experience of this investigator. This suggests that the arc character in a submerged arc is similar to that in an inert gas. Looking at the melting rate due to

resistance heating divided by that due to arc heating we find in the first equation a ratio of .26/1 and in the second .37/1. As mentioned above most of the melting is apparently due to the arc but resistance heating is significant. Of the total energy available about 15% is required to melt the electrode [10].

2.2 THE INFLUENCE OF THE WELDING PARAMETERS ON THE FLUX AND THE HAZ

Jackson and Shrubsall [19] have found that the fusion rate of the flux is proportional to the current and the voltage. This is not surprising since these two parameters determine the energy released by the welding power supply.

Signes and Baker [12] studied the effects of various welding conditions on the HAZ toughness. They compared toughness in welds made by single electrode submerged arc with; (i)multi electrode submerged arc,(ii)increased electrode extensions, (iii)cored electrodes and (iv)gas metal arc followed by submerged arc. The multi head or multi electrode technique caused more rapid cooling than the single electrode with the same total heat input. The increased stickout length was found to reduce penetration slightly but improved HAZ toughness significantly. The GMA/SMA combination reduced the time the HAZ spent above 1100 C (2000 F) consequently lessening HAZ coarsening. The other methods lower the total heat input for the same volume of deposited metal.

2.3 THE CHEMISTRY AND STRUCTURE OF THE WELD METAL

Compositional control has been found to produce dramatic improvements in weld toughness [5,6]. Silicon additions reduce the oxygen content and are of value when the upper shelf energy is impaired by inclusions.

Evans [22,7] and others have found manganese, molybdenum and nickel content to be very important to weld metal toughness. There appears to be an optimum content depending on the welding conditions. The elements Mn, Mo and Ni promote the formation of acicular ferrite but will also cause the formation of martensite if used in excess. A balance must be struck between a high level of the acicular ferrite and a safe level of strength increase. Dolby, Bonnet, and Kirkwood [7,23,24] have all found that oxygen must be present in the weld metal if acicular ferrite is to form. A very low level can result in martensite formation, which is beneficial for strength, but will also mean lower toughness. Bonnet [23] reports that oxygen levels of 40 ppm never produce acicular ferrite. Low levels of oxygen are common in the case of electron beam welds. By using an electron beam on the weld metal produced in the submerged arc process, however, acicular ferrite was still found. On the other hand, according to Bonnet, no acicular ferrite was found in the heat affected zone of the base plate. The conclusion drawn is that oxide

inclusions are required to nucleate acicular ferrite. The alloying elements serve to form the oxides and in some way retard or inhibit the formation of other microstrutural constituents such as proeutectoid or grain boundry ferrite [7,27]. It is still not true that just any oxide will cause this nucleation. The size and form of the inclusion must play a role [30].

The welding voltage can have important influence on the chemical composition of the resulting weld pool. Kirkwood [24] clearly shows that an increase in voltage in an open arc results in an increase in the oxygen and the nitrogen content. When welding with a submerged arc, however, he found a slight decrease in oxygen, and almost no change in nitrogen. It is clear that the increase in arc length caused by higher voltage allows more exposure of the filler material to the atmosphere. Why the submerged arc acts differently is perhaps explained by Chai [25]. He has proposed the existence of a "neutral point" for a given flux, base plate, electrode chemistry combination. The essence of his thesis is that given sufficient time, the equilibrium composition will form. The presence of a slag can alter the direction of chemical gradients, resulting in one case with the loss of an element to the slag and in another a net gain of the element to the weld. The dynamics of the reaction are dependent on the gradients of chemistry, ie. the magnitude of the driving forces, the temperature and the time when the reactions can

occur. The welding parameters are therefore important in determining the extent to which the weld metal achieves equilibrium with the slag and the electrode. Covering the arc with a molten slag will also aid in the reduction of atmospheric gas that is in contact with the arc plasma. If oxygen is to enter the arc region it must come, for the most part, from the molten slag. Control of oxygen in the weld metal has often been accomplished by proper flux formulation as well as additions of rare earth elements. Koukabi and North have investigated the cerium/oxygen relationship in submerged arc welding [26]. The cerium deoxidized the weld metal to as low as 100 ppm so that the oxygen content was nearly the same as the filler electrode.

Cochrane and Kirkwood [27], using dilatometer studies, determined a significant increase in the transformation temperature when acidic manganese-silicate fluxes were used. Basic fluxes are considered to generally produce more acicular ferrite than their acidic counterparts. Their study suggests that the type and size of the inclusions are different with the two fluxes. Bailey and Pargeter [28] conclude that the flux type influences C, Si, O, and S but not N and P. For the basic fluxes tested, they found very little difference.

3. EXPERIMENTAL

3.1 EXPERIMENTAL DESIGN

Welds were made at a voltage, current and travel speed determined by a Box-Behnken design as portrayed in figure 1. The Box-Behnken design is simply a system for choosing the values of the variables so that as few experimental points as possible need be used and yet still provide data from which predictions can be made. The points are selected to enclose the space in which predictions are desired, and for the variables chosen in this study the space consists of the dimensions i) voltage, ii)current and iii) travel speed (refer to table 3).

3.2 WELDING PROCEDURE

Submerged arc welds were made on 25 mm thick HY-80 plate as shown in figure 2. A 45 degree "V" joint was used with a root gap of approximately 10 mm. A 50 mm x 12 mm backing bar was placed under the joint and the plates were held by six gooseneck dogs to a welding table.

The surfaces of the backing bar and plate were ground smooth to remove paint, scale and rust. The preheat and interpass temperatures were maintained at 150 degrees C.

FIGURE 1

BOX-BEHNKEN DESIGN SPACE FOR THREE VARIABLES

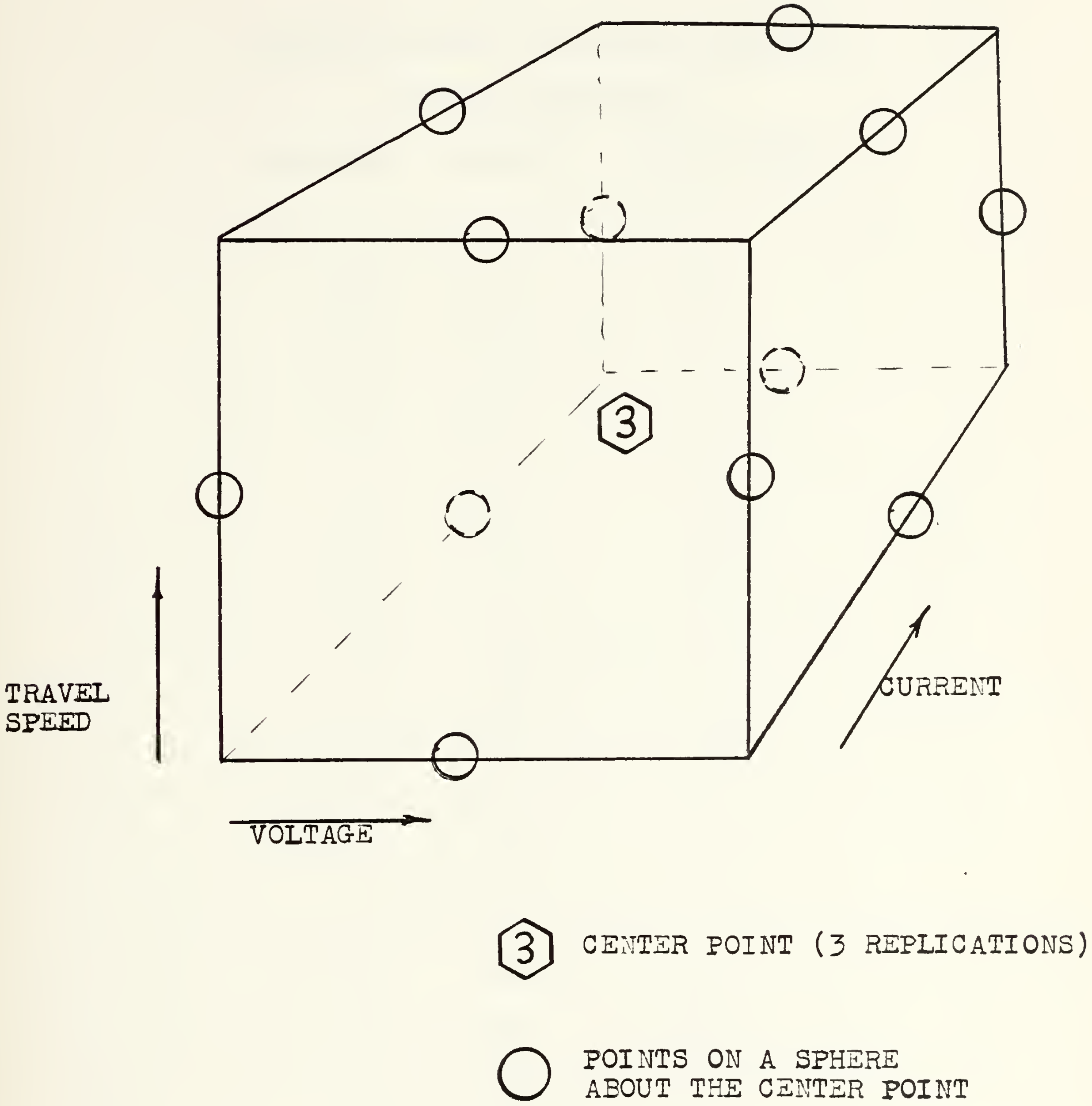

3
TRAVEL SPEED
VOLTAGE
CURRENT
3 CENTER POINT (3 REPLICATIONS)
POINTS ON A SPHERE ABOUT THE CENTER POINT

TABLE 3

THREE-VARIABLE BOX-BEHNKEN DESIGN

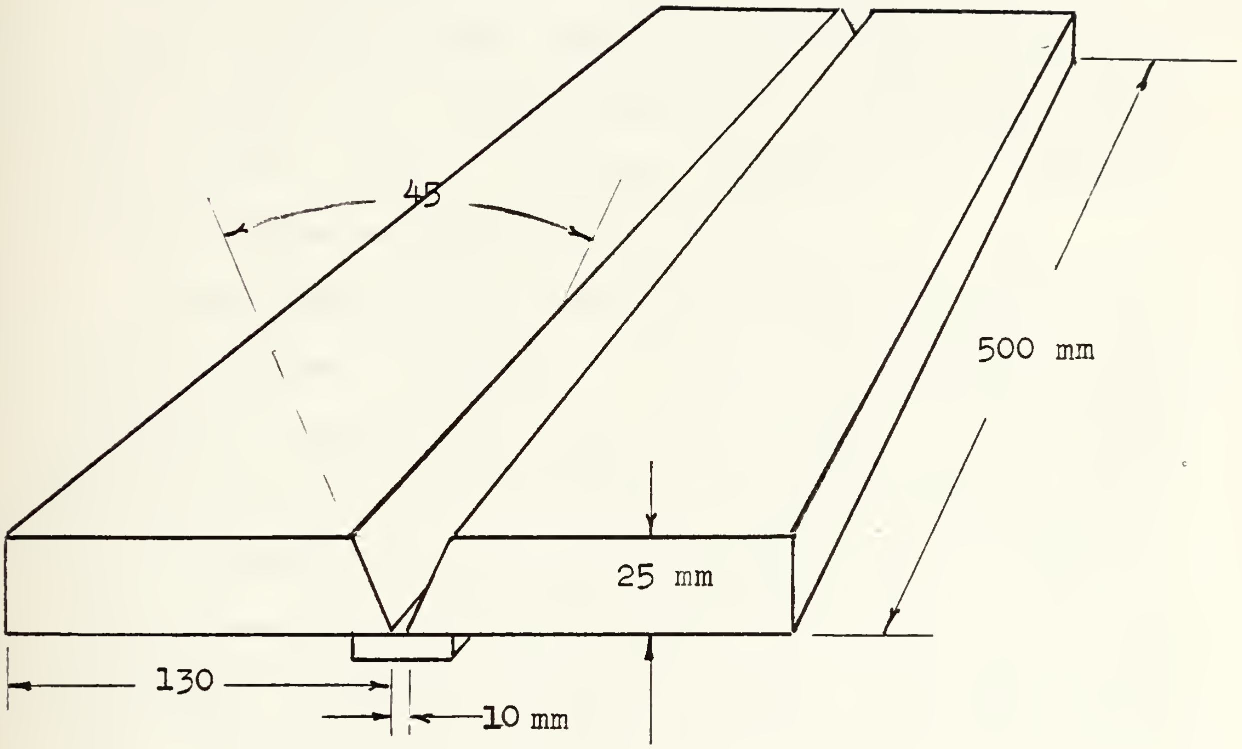
SCALED PARAMETERS

VOLTAGE	CURRENT	TRAVEL SPEED
+1.0	+1.0	0.0
+1.0	-1.0	0.0
-1.0	+1.0	0.0
-1.0	-1.0	0.0
+1.0	0.0	+1.0
+1.0	0.0	-1.0
-1.0	0.0	+1.0
-1.0	0.0	-1.0
0.0	+1.0	+1.0
0.0	+1.0	-1.0
0.0	-1.0	+1.0
0.0	-1.0	-1.0
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0

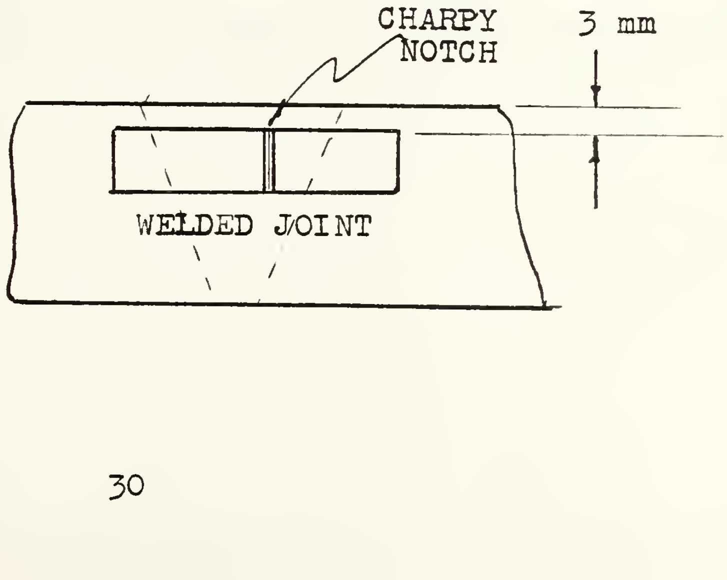
THE CENTER POINT (0,0,0) IS REPEATED THREE TIMES AND REPRESENTS IN THIS EXPERIMENT 33 VOLTS, 500 AMPS, AND 15 IN/MIN

FIGURE 2

JOINT GEOMETRY AND DIMENSIONS



BACKING BAR 50 x 12 mm



The flux was heated in an electric oven for at least 24 hours at 200 degrees C to remove moisture. Unfused flux was recovered after each pass by sifting thru a number 12 ASTM screen mesh (1.70 mm opening).

Welding was accomplished using a Linde V1-800 CV/DC power supply with a UCC-8 controller, and Linde EH-10 wire feeder head. A Union Carbide "J" governor controlled the welding travel speed.

Temperature measurements of the plate were made using a lacquer (TEMPILAQ). Voltage was checked with a calibrated digital voltmeter and welding current was monitored with a shunt resistor. Welding travel speed was controlled by a DC motor previously calibrated by actual timed-distance measurements. Welding current was controlled indirectly by adjusting the electrode feed rate. The electrode extension was maintained at 19 mm (.75 inches). Voltage, travel speed, extension and electrode feed rate were within 3 % of the desired values, but current was observed to fluctuate by 10 %. The polarity was D.C. reverse (electrode positive).

3.3 TESTING AND EXAMINATION

Pads were saw cut and ground by General Dynamics Electric Boat Division. The pads were etched to reveal the weld and the notch was located near the center of a weld pass within 3 mm of the plate upper surface. Three Charpy samples for each of the thirty welds made were broken at -50 degrees C (-60 F).

The broken Charpy specimens were used to obtain weld metal composition by emission spectroscopy and vacuum fusion for oxygen content. One broken sample from each weld was mounted and polished for optical and scanning electron microscope studies. An energy dispersive X-ray spectrometer (EDAX) was used to qualitatively determine the composition of inclusions found on the polished surface of the Charpy specimens and a sample of the base plate. Polished samples were examined under the optical microscope both before and after etching with 1% Nital.

Samples of the fused and unfused fluxes were also examined and chemically tested using the X-ray method noted above.

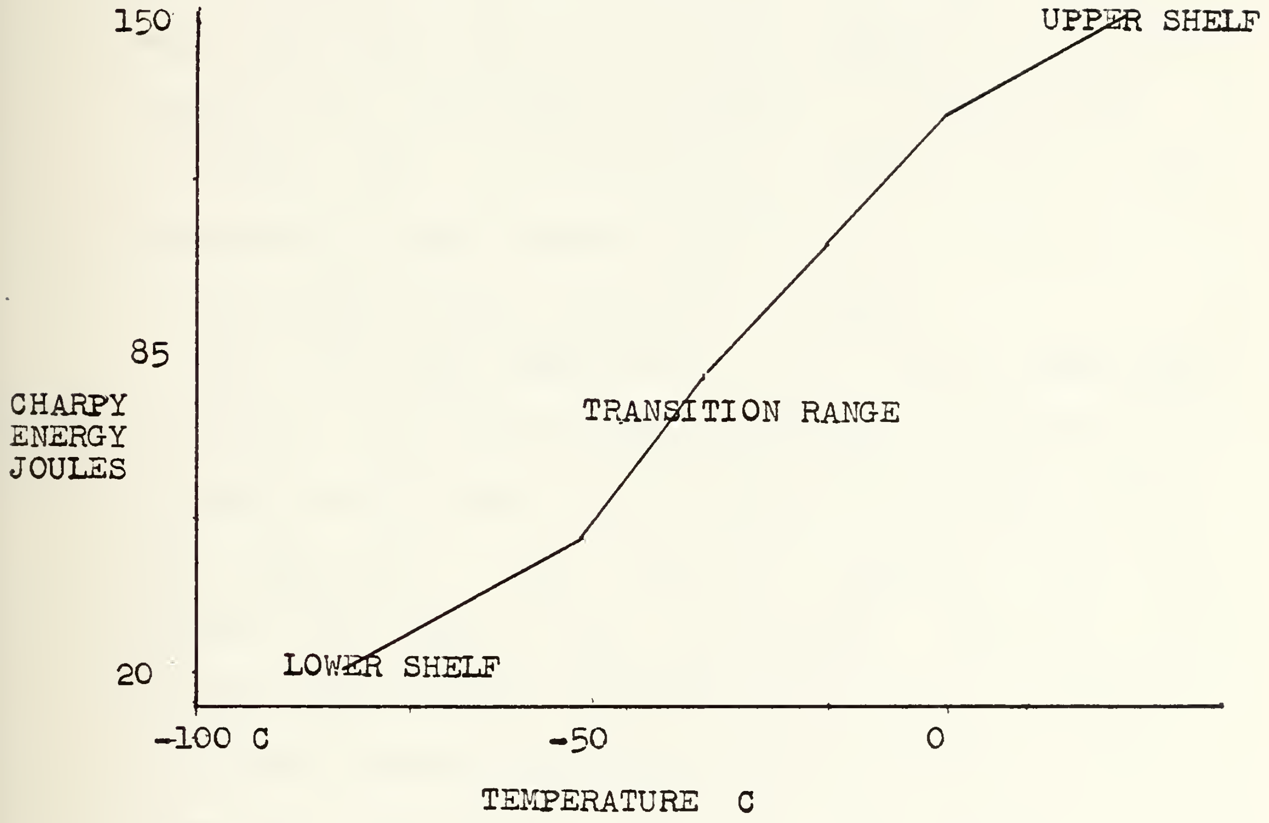
4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 REGRESSION PREDICTING TOUGHNESS

The design of the experiment has provided an excellent basis for determining toughness of welds made in the ranges of voltage, current and travel speed tested. In addition to pointing to the optimum conditions, a measure of the error can also be made. The "error" is the difference one expects to find in the Charpy energy predicted based on the curve fitted to the test data. Because the regression was performed using least squares, every experimental point (each Charpy bar tested) carries equal weight. The variability in Charpy energies is noticeably large in the ductile brittle transition range. The exact temperature of the transition is not known for these tests because only a single temperature was used, although the temperature was chosen such that the fracture occured near the transition. It is clear that any curve fitted to data based on Charpy bars broken at a single temperature will most likely contain large variations that reflect the bi-modal nature of the test in the transition range [refer to figure 3].

FIGURE 3

TYPICAL CHARPY FRACTURE ENERGY CURVE
FOR HY-80 WELD METAL



4.2 FRACTURE TOUGHNESS TESTS

The Charpy test is useful as a comparison between welds made with a particular type of steel, it is not, however, a convincing way to compare welds made on different steels. Other tests, such as the COD (Crack Opening Displacement) J-curve and R-curve measurements have been developed to better compare different materials, and also aid in design [20,21]. One cannot assume that a given Charpy energy will be sufficient in a design, but it is clear that a higher value is more desirable if other factors are equal.

4.3 ANALYSIS OF REGRESSION ACCURACY

It is perhaps important to note that the experimental work has been directed towards correlating the variables of voltage, current and travel speed to fracture toughness. Any fracture toughness test will suffice as long as the differences that the test measures due to the controlled experimental parameters are great enough to be seen over pure error. The pure error is the scatter in the test itself which in the case of Charpy measurements can be significant. A measurement of the pure error can only be made by repeating the experiment. This has been done in two ways. Firstly, each weld made was tested three times (three Charpy bars). Secondly, three of the fifteen welds made with each flux were welded under the same conditions at times randomly selected during the welding program.

The data show some very large variations in the measured Charpy energies, 68 Joules (50 ft lbs) in one case for example. Generally the variation is much less (about 16-20 J (12-16 ft lbs) on average) [refer to tables 4, 5]. It is impossible to perform a regression that will account for pure error but the pure error, if known, will provide limits of the regression accuracy. The pure error has been measured and shows that the regression model used predicts 56% of the variability (for the worst case using Lincoln 880) [refer to tables 6,6A]. The pure error was 35% leaving only 9% unexplained. Simply stated, if there were no error or variation in the Charpy measurement, the Charpy value could be almost exactly predicted by voltage, current and travel speed 91 times out of 100 specimens. Since the Charpy energy does vary for the same welding conditions, the model can only be useful for predictions in a statistical sense. This conclusion is not new and only requires a better test if one wishes to improve the quality of the prediction. Even though the regression will be of statistical value only, this reflects the nature of any process that contains unexplained variations or depends on a great many factors that cannot be easily measured. The independent variable that was held "constant" may in fact be changing.

TABLE 4 WELD DATA FOR LINCOLN 880

TEST	VOLTS	AMPS	TRSP in/min	HEAT KJ/in	CV* ftlb	DILUTION(Cr) % Base plate
2	33	500	15	66.0	45	20
					84	
					34	
3	30	500	12	75.0	50	31
					50	
					46	
4	30	500	18	50.0	83	17
					93	
					80	
5	33	400	12	66.0	37	21
					47	
					32	
6	33	400	18	44.0	62	14
					63	
					43	
7	33	600	12	99.0	76	31
					76	
					71	
8	33	600	18	66.0	78	23
					96	
					77	
9	36	500	12	90.0	43	28
					46	
					43	
10	36	500	18	60.0	42	28
					58	
					39	
11	33	500	15	66.0	76	21
					91	
					66	
12	36	600	15	86.4	79	39
					83	
					61	
13	30	400	15	48.0	48	15
					50	
					38	
14	30	600	15	72.0	62	39
					77	
					54	
15	33	500	15	66.0	80	25
					99	
					65	
16	36	400	15	57.6	54	27
					55	
					36	

*First value listed was from the Charpy specimen which was chemically analysed. The remaining two are CV energies of additional specimens from the same weld.

TABLE 5 WELD DATA FOR OP 121 TT

TEST	VOLT	AMPS	TVSP in/min	HEAT KJ/in	CV* ftlb	% DILUTION(Cr) Base plate
17	33	500	15	66.0	71 75 68	23
18	30	500	12	75.0	52 59 49	28
19	33	400	12	66.0	48 48 46	19
20	33	400	18	44.0	64 81 64	32
21	33	600	12	99.0	46 51 44	25
22	33	600	18	66.0	72 64 79	27
23	36	500	12	90.0	60 69 50	30
24	36	500	18	60.0	71 73 67	17
25	33	500	15	66.0	86 88 66	29
26	36	600	15	86.4	61 65 60	35
27	30	400	15	48.0	52 58 41	18
28	30	600	15	72.0	75 85 74	42
29	36	400	15	57.6	51 57 41	18
30	33	500	15	66.0	57 64 53	36
31	30	500	18	50.0	89 93 85	22

*First value listed was from the Charpy specimen which was chemically analysed. The remaining two are Charpy energies of additional specimens from the same weld.

TABLE 6

EQUATIONS PREDICTING CHARPY VALUE BASED ON REGRESSION ANALYSIS USING THE SCALED VALUES OF VOLTAGE(V), CURRENT(I) AND TRAVEL SPEED(T)

$$CV\ (\text{ft lbs}) = X0 + X1(V) + X2(I) + X3(T) + X4(V \times I) + X5(V \times T) + X6(I \times T) + X7(V^2) + X8(I^2) + X9(T^2)$$

WHERE 30 TO 36 VOLTS IS SCALED TO -1 TO 1
400 TO 500 AMPERES IS SCALED TO -1 TO 1
12 TO 18 IN/MIN IS SCALED TO -1 TO 1

COEFFICIENT	LINCOLN 880	OP121TT
X0	71.1111	69.7778
X1	-3.8333	-3.6250
X2	13.5417	5.2083
X3	8.2083	11.6667
X4	1.7500	-3.8333
X5	-8.5833	-6.2500
X6	-2.0000	0.5833
X7	-10.0556	-.3056
X8	-2.9722	-9.4722
X9	-4.9722	-1.3889
R-SQUARED	56.3%	68.8%
PURE ERROR	34.7%	24.6%
LACK OF FIT	9.0%	6.6%
STANDARD DEV OF PREDICTION (FT LBS)	13.88	8.72

TABLE 6 A

	LINCOLN 880	OP121TT
R-SQUARED	56.3%	68.8%
VARIABLE	% OF R-SQUARED	% OF R-SQUARED
VOLTAGE	4.1%	5.4%
CURRENT	50.6%	11.1%
TRAVEL SPD	18.6%	55.5%
VOLTSxAMPS	0.4%	3.0%
VOLTSxTRAV SPD	10.2%	8.0%
AMPSxTRAV SPD	0.6%	0.1%
VOLTS SQUARED	11.6%	NIL
AMPS SQUARED	0.9%	16.6%
TRAV SPD SQUARED	3.2%	0.4%

The percentages in each column reflect the importance of the terms used in the regression to predict the toughness assuming all the terms are independant.

This was the case with current during all of the welding reported here. The electrode feed rate was the variable actually held constant while the current was seen to fluctuate widely. This variation was on the order of 10%, or +/- 50 amperes. When it is realized that current variations chosen for the experiment are of the same order, it is not surprising that the regression analysis will not give excellent results. It is a false pretense to assume that current was fixed for any given weld, but the fluctuations do not produce a bias error and the average value is still meaningful for use as a regression variable. Fortunately the variables of voltage and travel speed could be better controlled during the experiment (within 3%). One of the principal reasons for conducting any experiment is to determine the importance of variations in the parameters . It is clear that current is found to be important in spite of the variations that were noted during welding. It is in part due to the manner in which the parameters were chosen that the unwanted variations in current do not seriously impair the validity of the regression. In addition the current fluctuations were rapid compared to the travel speed and multi-pass welding will also smooth the effect.

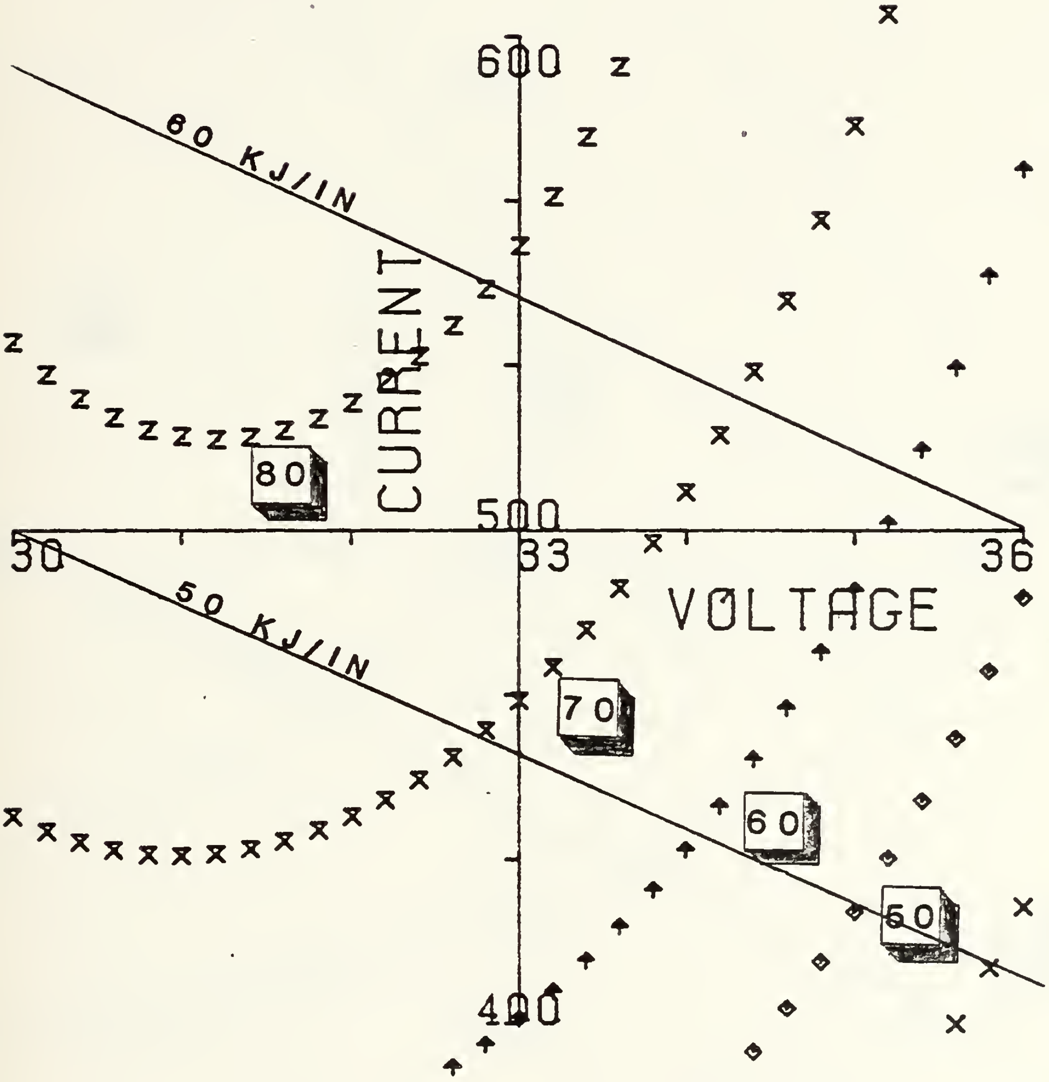
The regression shows significant variations in Charpy energy with each variable. Generally the best toughness is obtained when both current and travel speed are high, ie. 600 amperes, 18 inches per minute (7.6mm/sec) [refer to figures 4 and 5]. The optimum conditions are not, however, exactly the same for both fluxes. Heat input is not seen to be significant in the range of 2-4 KJ/mm (50 to 100 KJ/IN). The importance of heat input has often been mentioned in the literature, but heat input alone has not proven in this study to be the key to a good or a bad weld. It is true that high heat input will increase the problems associated with the heat affected zone, and the width of the HAZ does show positive correlation with heat input [refer to figure 6]. The properties of the HAZ were not measured in this investigation but must be considered when judging the benefits of a parameter optimization based solely on the weld metal toughness.

Another concern when applying experimental results to a production process such as welding is that laboratory experiments are usually much better controlled than production work. Welding conditions during the fabrication of a structure cannot be as easily controlled, nor can the full range of variables be easily monitored. One goal is to make the process as insensitive as possible to the variations that are difficult or expensive to control, and another to

ISO CHARPY ENERGY

LINCOLN 880

FIGURE 4



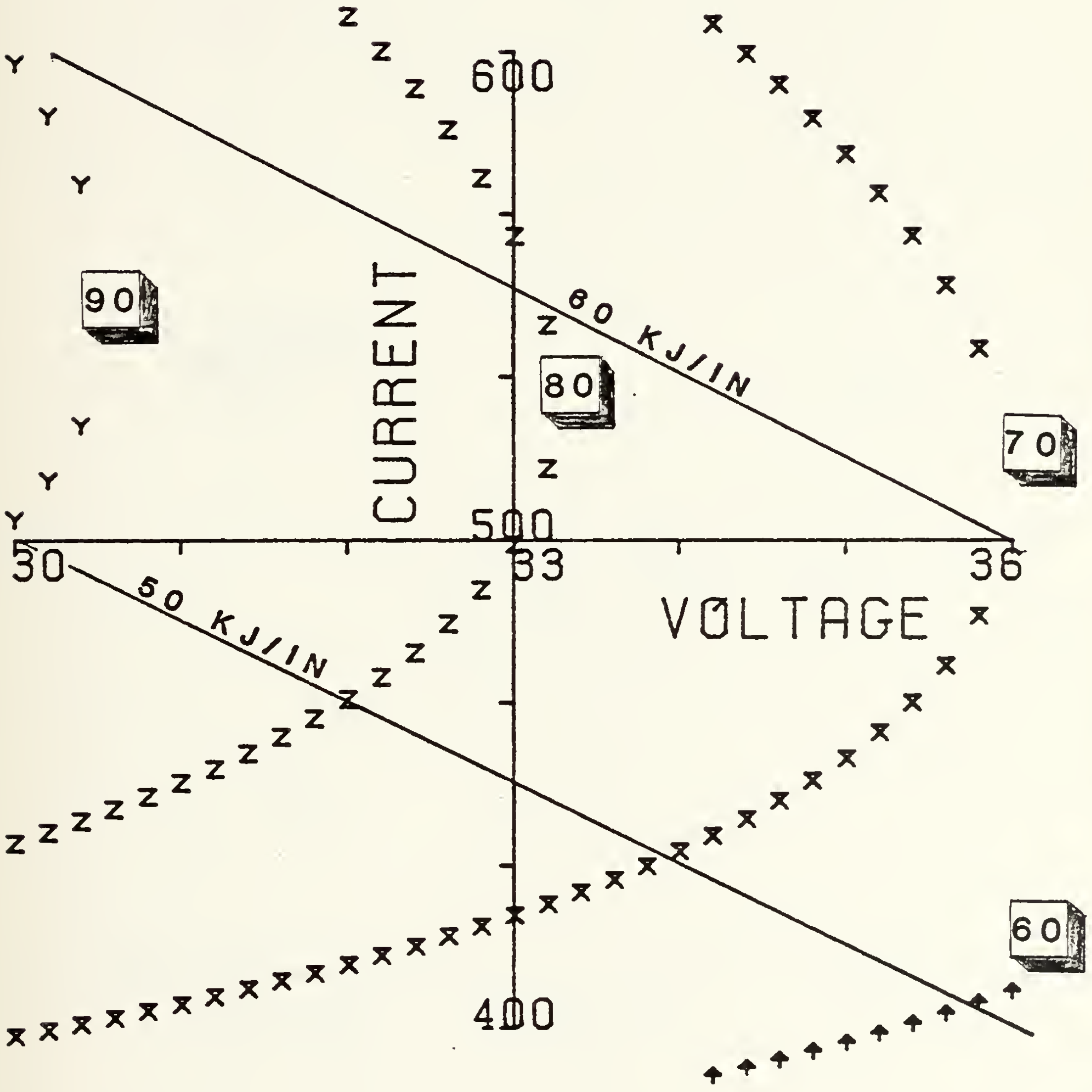
TRAVEL SPEED 18 in/min

Cv ENERGY IN FT-LBS

ISO CHARPY ENERGY

OP 121 TT

FIGURE 5

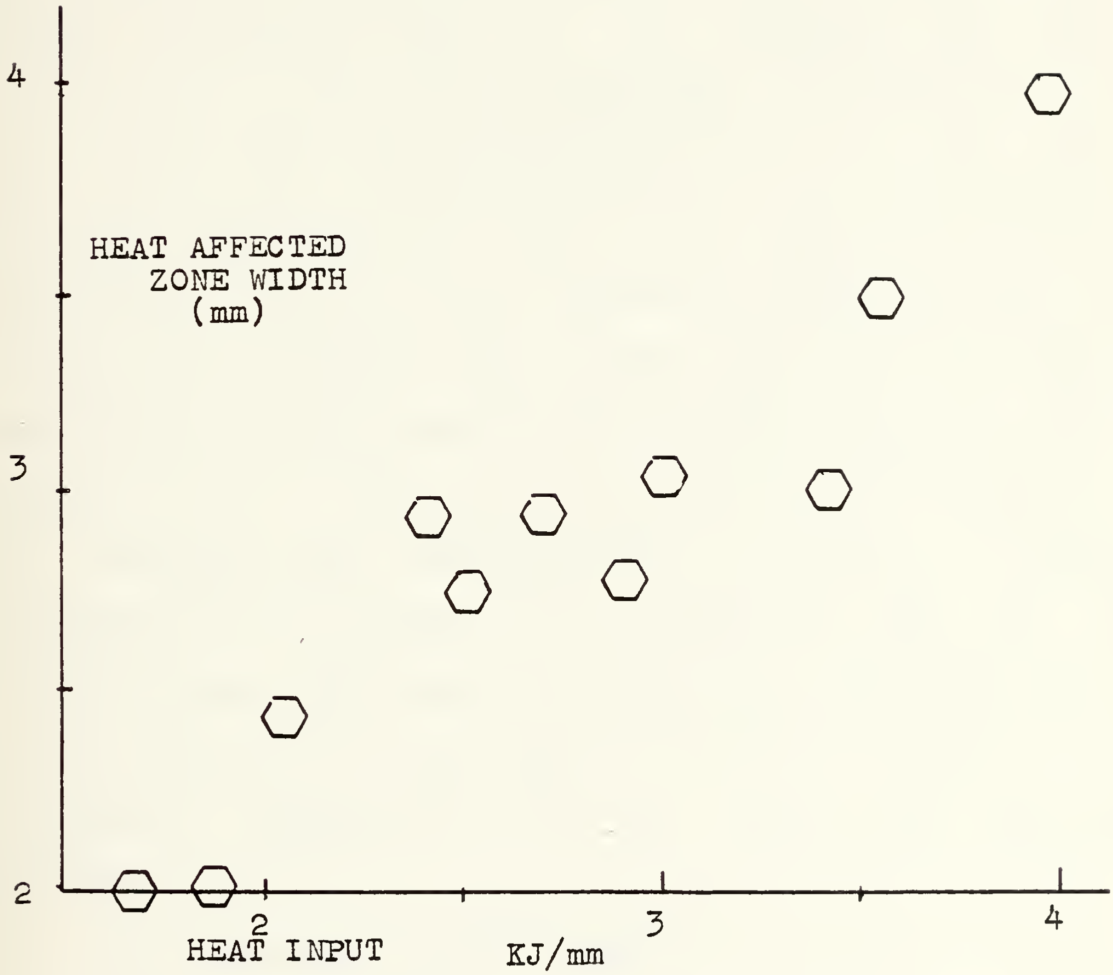


TRAVEL SPEED 18 in/min
Cv ENERGY IN FT-LBS

FIGURE 6

HEAT AFFECTED ZONE WIDTH

VERSUS HEAT INPUT



identify those parameters that are most significant in the production of a good weld and which must be controlled.

The prediction of thoughness based on an empirical study limits the usefulness of this work. Specifically, the validity of any prediction outside the experimental space is open to question. The toughness has been correlated to the welding parameters and does appear to be valid, but the equations that fit this data will probably not do as well with a wider range of welding variables. The fit of the regression model was seen to deteriorate markedly when the data provided by Electric Boat Division was combined with the data from the welds made at M.I.T. This serves to point out the difficulty in assessing the importance of variables. Slight differences in base plate chemistry may be of significance. The study presented here cannot determine this effect, or for that matter any effect caused by the variables assumed to be fixed during the testing program.

4.4 THE EFFECT OF ARC LENGTH

The experimental program described here has attempted to determine the effects of voltage, current and travel speed. The voltage produced by the power supply at the welding head is equal to the total voltage drop across the arc, and electrode. As noted earlier,

the voltage can alter the quantity of oxygen entering the weld metal. This effect is most likely due to the actual length of the arc. A longer arc will mean an extended time of flight for the metal drops pinched off from the electrode. If any reaction occurs in this time period, it will have more time to reach equilibrium. One reaction that is taking place is the transfer of Mn. Recalling Chai [25], it is clear that the Mn in the weld pool and metal droplets in the spray will tend to pass into the slag when no Mn exists in the flux. This must be so because of the chemical gradient. Experimental evidence shows that the Lincoln 880 flux has little or no Mn whereas the OP121TT contains 2 % MnO. There is a clear difference in the average Mn content of the weld metal made with the two fluxes [refer to tables 7,8]. The welds made with Lincoln 880 contain on average 0.2 % less Mn than the welds made using OP121TT. The electrode contains 1.31 % Mn and if none were lost to the slag it should mix with the base plate and produce a weld with a concentration of Mn given by

$$\%Mn(weld) = X(\%Mn \text{ in base plate}) + (1-X)(\%Mn \text{ in electrode})$$

where X = dilution caused by the base plate
assuming no previous dilution

In order to determine the dilution, the content of Cr in the weld has been compared with that of the base plate and electrode. This is shown in tables [9,10] and produces a reasonable lower limit for dilution. This is only a lower limit because Cr will also be lost to the

TABLE 7 WELD COMPOSITION DATA WITH LINCOLN 880

TEST	VOLT	AMPS	TVSP *	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	O
2	33	500	15	.047	.47	.89	.013	.005	.32	2.05	.41	.063	.018	.031
3	30	500	12	.054	.45	.80	.012	.006	.47	2.06	.39	.065	.019	.038
4	30	500	18	.068	.45	.92	.010	.005	.29	2.02	.41	.055	.012	.036
5	33	400	12	.077	.44	.86	.010	.005	.33	2.00	.41	.061	.009	.028
6	33	400	18	.068	.46	.90	.010	.004	.25	1.97	.42	.056	.015	.035
7	33	600	12	.087	.40	.84	.008	.005	.47	1.99	.38	.065	.010	.029
8	33	600	18	.052	.47	.99	.012	.005	.36	2.06	.41	.064	.020	.036
9	36	500	12	.087	.40	.82	.009	.005	.42	2.01	.40	.068	.008	.029
10	36	500	18	.056	.46	.84	.011	.006	.43	2.08	.40	.066	.018	.030
11	33	500	15	.045	.47	.92	.013	.006	.33	2.06	.41	.063	.018	.041
12	36	600	15	.086	.40	.78	.010	.006	.57	2.05	.36	.090	.009	.006
13	30	400	15	.046	.48	.91	.015	.005	.26	2.06	.42	.062	.021	.039
14	30	600	15	.070	.44	.88	.011	.006	.57	2.08	.36	.063	.020	.044
15	33	500	15	.071	.46	.85	.012	.005	.39	2.05	.40	.082	.010	.039
16	36	400	15	.055	.44	.80	.014	.005	.41	2.09	.40	.068	.016	.039
MEAN VALUES				.065	.44	.87	.011	.005	.39	2.04	.40	.066	.015	.035
STANDARD DEV				.015	.03	.06	.002	.001	.10	0.04	.02	.009	.005	.005

* TRAVEL SPEED IN INCHES/MIN.
CHEMICAL COMPOSITIONS IN WEIGHT PERCENT

TABLE 8 WELD COMPOSITION DATA WITH OP121TT

TEST	VOLT	AMPS	TVSP	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	O
17	33	500	15	.053	.44	1.10	.015	.006	.36	2.04	.40	.068	.018	.034
18	30	500	12	.058	.44	1.03	.015	.006	.43	2.04	.39	.070	.017	.036
19	33	400	12	.044	.44	1.10	.017	.005	.31	1.97	.40	.065	.015	.041
20	33	400	18	.110	.31	0.90	.017	.005	.48	2.03	.37	.086	.008	.041
21	33	600	12	.110	.33	0.99	.017	.005	.39	2.02	.39	.084	.012	.040
22	36	600	18	.051	.43	1.02	.014	.005	.41	1.99	.39	.072	.021	.037
23	36	500	12	.051	.41	0.99	.016	.005	.45	2.00	.38	.074	.016	.031
24	36	500	18	.053	.35	1.11	.017	.010	.29	1.99	.40	.074	.010	.040
25	33	500	15	.047	.41	0.98	.015	.005	.44	1.98	.38	.075	.017	.035
26	36	600	15	.081	.38	0.91	.016	.005	.52	2.04	.36	.073	.009	.033
27	30	400	15	.049	.46	1.10	.015	.010	.30	1.99	.40	.059	.019	.050
28	30	600	15	.087	.38	0.84	.015	.006	.61	2.02	.35	.090	.009	.044
29	36	400	15	.045	.42	1.13	.016	.004	.30	1.99	.40	.083	.008	.041
30	33	500	15	.077	.39	0.93	.018	.005	.53	2.02	.36	.100	.010	.033
31	30	500	18	.045	.42	1.10	.017	.004	.35	1.99	.39	.086	.010	.050
MEAN VALUES				.064	.40	1.02	.016	.006	.41	2.01	.38	.077	.013	.039
STANDARD DEV.				.023	.04	0.09	.001	.002	.10	0.02	.02	.011	.005	.006

TRAVEL SPEED IN INCHES/MIN
CHEMICAL ANALYSIS IN WEIGHT PERCENT

TABLE 9 WELD DATA FOR LINCOLN 880

TEST	VOLT	AMPS	TVSP	CV	NR. OF PASSES	APPROXIMATE ELECT.FD RATE	CALCULATED DILUTION	
							(Cr)	(Ni)
2	33	500	15	45	13	130 in/min	.20	.50
3	30	500	12	50	7	120	.31	.55
4	30	500	18	83	13	130	.17	.38
5	33	400	12	37	11	90	.21	.29
6	33	400	18	62	21	85	.14	.18
7	33	600	12	76	7	175	.31	.25
8	33	600	18	78	13	175	.23	.55
9	36	500	12	43	7	120	.28	.34
10	36	500	18	42	11	120	.28	.63
11	33	500	15	76	11	130	.21	.55
12	36	600	15	79	7	160	.39	.50
13	30	400	15	48	14	100	.15	.55
14	30	600	15	62	9	190	.39	.63
15	33	500	15	80	11	130	.25	.50
16	36	400	15	54	16	100	.27	.67
MEAN VALUES				61			.26	.47
STANDARD DEV				16			.08	.15

DILUTION BASED ON THE MEASURED CHROMIUM AND NICKEL CONTENTS OF THE WELD METAL

$$\text{Dilution} = \frac{[\%M(\text{weld metal}) - \%M(\text{electrode})]}{[\%M(\text{base plate}) - \%M(\text{electrode})]}$$

Where M is Cr or Ni content

TABLE 10 WELD DATA FOR OP121TT

TEST	VOLT	AMPS	TVSP	CV	NR. OF PASSES	APPROXIMATE ELECT.FD.RATE	CALCULATED DILUTION (Cr)	(Ni)
17	33	500	15	71	10	130 in/min	.23	.46
18	30	500	12	52	7	120	.28	.46
19	33	400	12	48	10	90	.19	.17
20	33	400	18	64	18	85	.32	.42
21	33	600	12	46	7	175	.25	.38
22	36	600	18	72	9	175	.27	.25
23	36	500	12	60	9	120	.30	.29
24	36	500	18	71	15	120	.17	.25
25	33	500	15	86	11	130	.29	.21
26	36	600	15	61	9	160	.35	.46
27	30	400	15	52	15	100	.18	.25
28	30	600	15	75	9	190	.42	.38
29	36	400	15	51	15	100	.18	.25
30	33	500	15	57	11	130	.36	.38
31	30	500	18	89	13	130	.22	.25
MEAN VALUES				64			.27	.32
STANDARD DEV				13			.08	.10

DILUTION BASED ON THE MEASURED CHROMIUM
AND NICKEL CONTENTS OF THE WELD METAL

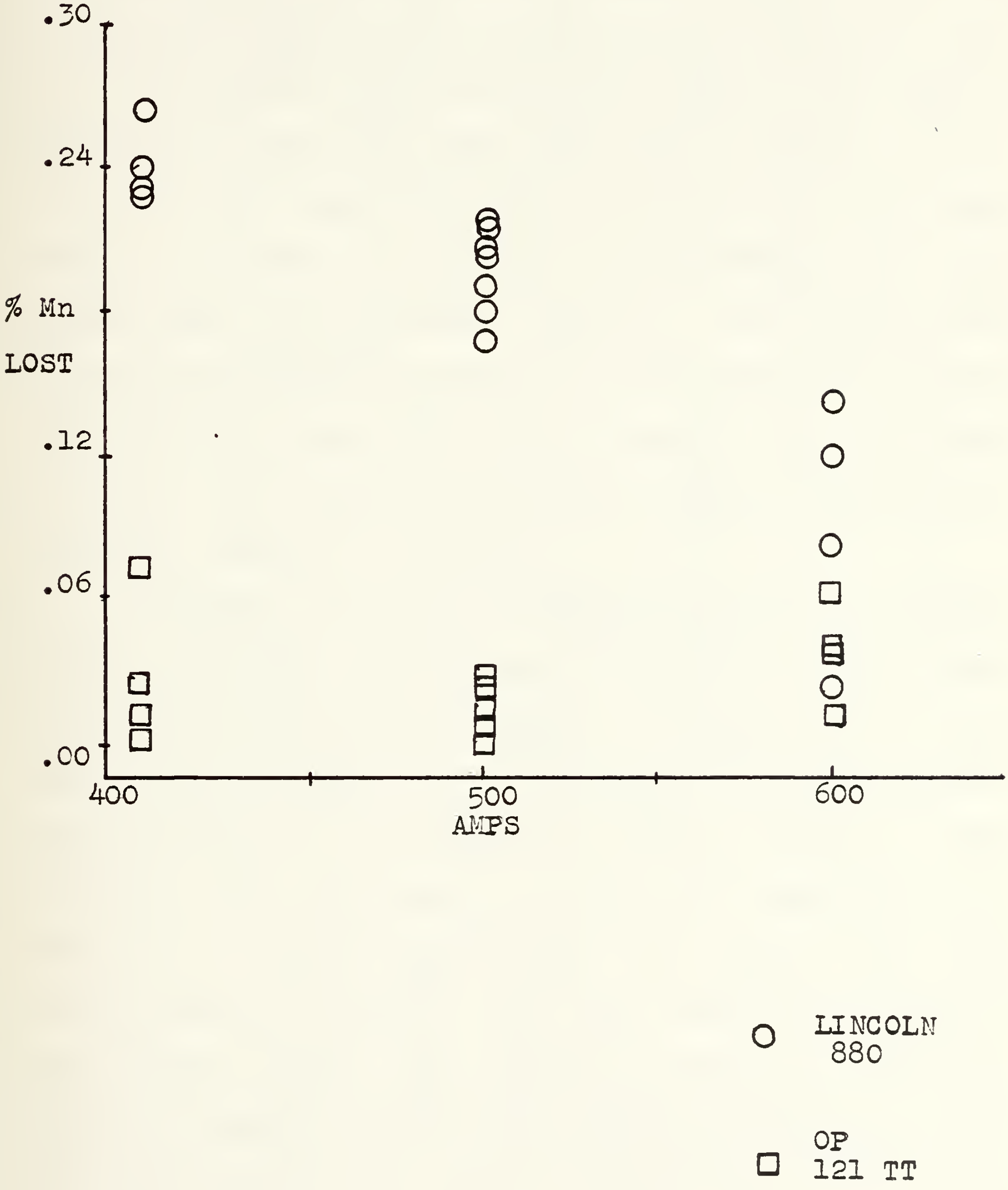
$$\text{Dilution} = \frac{[\%M(\text{weld metal}) - \%M(\text{electrode})]}{[\%M(\text{base plate}) - \%M(\text{electrode})]}$$

Where M is Cr or Ni content

slag, but it will not be lost to any extent while passing thru the arc since the Cr content is very much lower in the electrode (0.066% compared to 1.35%). The "base plate" is actually already diluted from earlier passes also causing the value of dilution to be underestimated. The difference between the actual weld metal Mn content and that expected from dilution will be the Mn lost to the slag. A plot of Mn lost to the slag verses welding current has been made for the welds produced under Lincoln 880 [refer to figure 7]. There is a clear correlation between the current and the Mn lost. With higher current less Mn is lost. Increasing the current will cause the arc length to fall (voltage drop across the electrode is increased) so that less time is available for any loss to occur. No correlation could be seen when examining the same plot for welds made with OP121TT. The explanation for this disparity appears to be the MnO in the OP121TT formulation. The amount of Mn lost to the slag was in fact very low in the case of OP121TT (less than 0.1%). The neutral point for the Mn reaction should be in the range of 1%-2% according to Chai [25]. When welding with OP121TT all of the reaction components (weld metal, flux and electrode) fall within these limits. The fact that so little Mn is lost to the slag with this flux is explained by the low concentration gradient of Mn and the near equilibrium condition as measured by the neutral point.

FIGURE 7

MANGANESE LOST TO THE SLAG
AS A FUNCTION OF WELDING CURRENT



4.5 ANALYSIS OF THE FLUXES

While the general chemical makeup of the two fluxes is known, it is surprising to observe the rather large variations found in the literature [refer to table 11]. It is extremely difficult to fully identify the form of the minerals that have been combined to produce a flux. In addition, batch to batch variations can occur and there is reason to believe that LINCOLN may have experienced this problem recently. The unexplained variations between two groups of welds made with Lincoln 880 [refer to table 12] seems to support this. In sharp contrast are the welds made with OP121TT which give identical results on average.

Electron microscope examination of the flux grains shows only minor differences. The OP121TT grains have larger particles bonded together in comparison to the 880 [refer to figures 8,9]. Another difference was the presence of Na in the 880 which was not found in the OP121TT. In the same way, K was only detected in the OP121TT. These observations do suggest that the binders may be different, but they cannot be considered conclusive because the chemical analysis technique (EDAX) is unable to probe very deeply into the grain and can only measure near surface composition. The grains can be very nonhomogeneous as was apparent when Mg was initially not detected on the OP121TT grains. Since

TABLE 11 REPORTED FLUX COMPOSITIONS

COMPOUND	LINCOLN 880 WT PERCENT		OP121TT WT PERCENT			
ANALYSIS	(A)	(B)	(C)	(D)	(E)	(F)
REFERENCE	[31]	[33]	[32]	[30]	[34]	[35]
SiO_2	16.0	13.9	15.6	13.5	13.4	15.0
MnO	NONE	NONE	1.9	1.8	0.9	? *
CaO	3.0	2.1	7.0	8.0	11.0	? *
MgO	27.0	26.3	25.7	43.6	40.0	? *
Al_2O_3	22.0	22.7	19.2	18.1	14.2	? *
TiO_2	2.0	NONE	1.1	1.0	0.5	? *
CaF_2	22.0	22.7	26.5	20.99	14.4	25.0
ZrO_2	4.0	7.4	NONE	0.2	NONE	NONE
FeO	NONE	1.0	NONE	NONE	1.7	NONE
Na_2O	NONE	2.0	NONE	NONE	0.9	NONE
K_2O	NONE	NONE	NONE	0.2	0.8	NONE
BaO	NONE	NONE	NONE	NONE	0.1	NONE

$$* \ SiO_2 + TiO_2 = 15.0$$

$$CaO + MgO = 35.0$$

$$Al_2O_3 + MnO = 20.0$$

The above analyses are from the literature and have in most cases been based on the assumption that all the elements are in an oxide form. This assumption therefore will not show the presence of the binding agent which is probably a potassium or sodium silicate. The actual form of the compounds is most likely much different, for example it is known that Lincoln 880 contains ZrO_2 as a zirconium silicate.

TABLE 12

COMPARISON OF CHARPY ENERGIES BASED ON VARIOUS SETS OF DATA

DATA BASE	NR. OF CHARPY BARS SAMPLED	MEAN CV FT LBS(-60F)	STANDARD DEV FT LBS	FLUX TYPE
MIT WELDS	45	61.5	18.73	LINCOLN 880
MIT WELDS	45	63.8	13.94	OP 121 TT
ELECTRIC BOAT	42	34.2	15.56	LINCOLN 880
ELECTRIC BOAT	40	64.0	12.26	OP 121 TT

WELDS MADE AT ELECTRIC BOAT WERE ACCOMPLISHED UNDER SIMILAR CONDITIONS WITH HEAT INPUTS 2.0 TO 4.3 KJ/MM. ELECTRODE STICKOUT FOR E.B. WAS 25 MM INSTEAD OF 19 MM

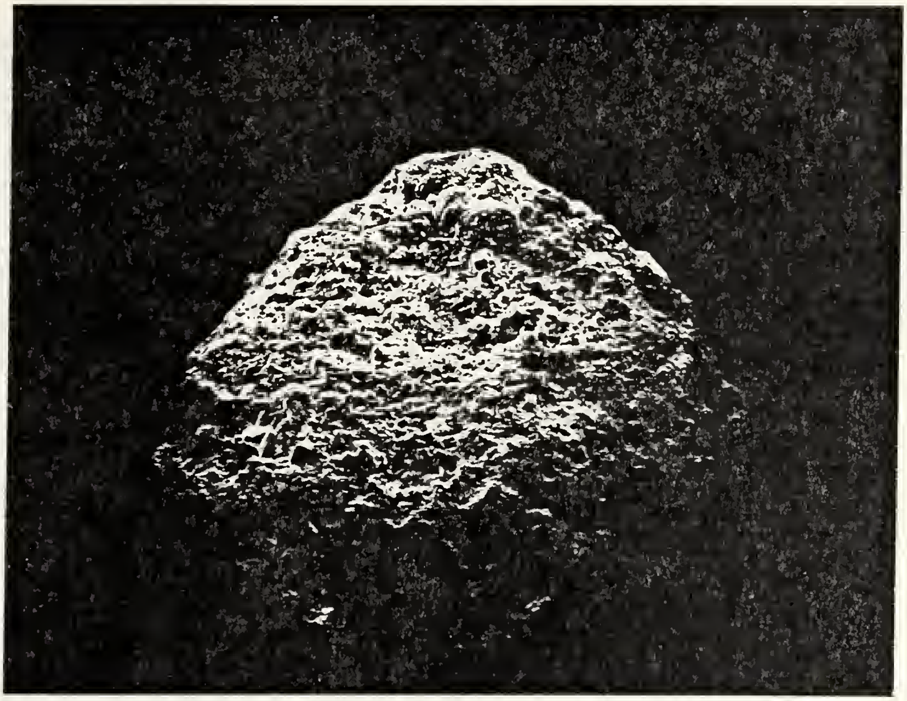


Figure 8 a Lincoln 880 flux grain (X 50)

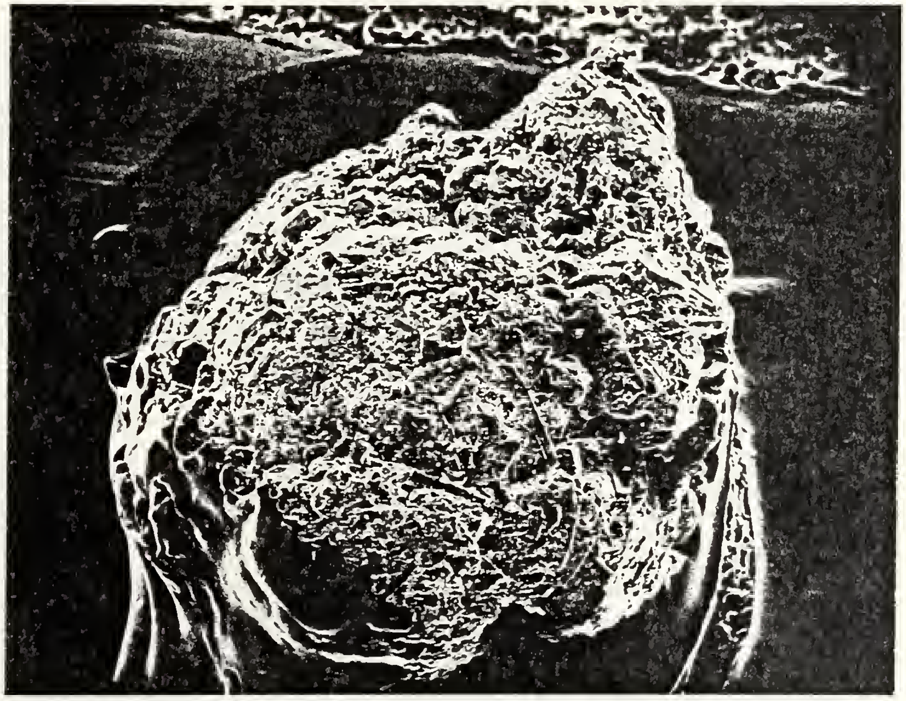


Figure 8 b OP 121 TT flux grain (X 50)

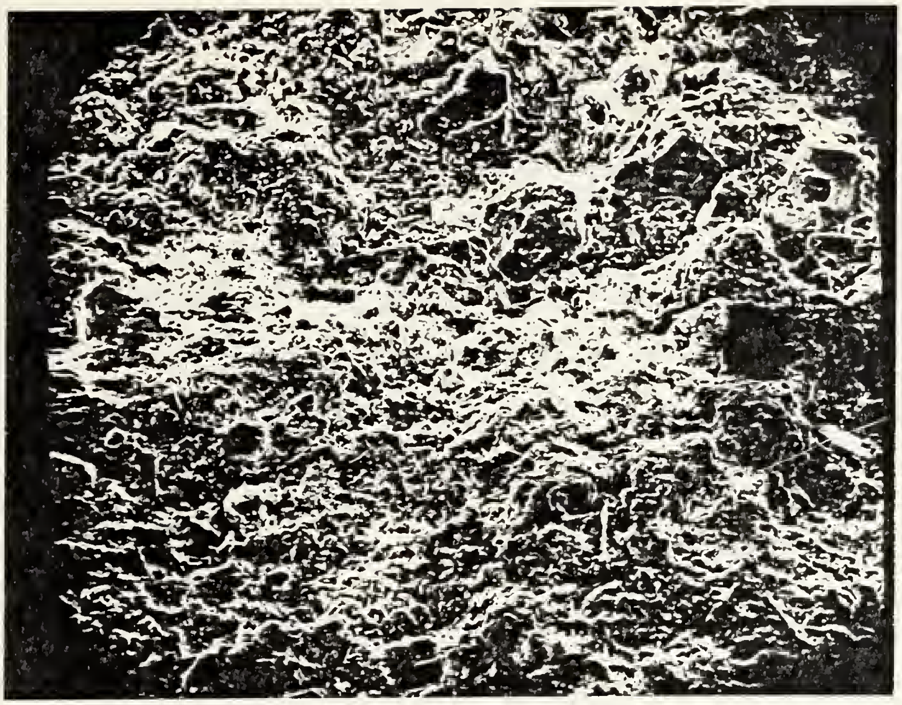


Figure 9 a Lincoln 880 flux grain (X 200)

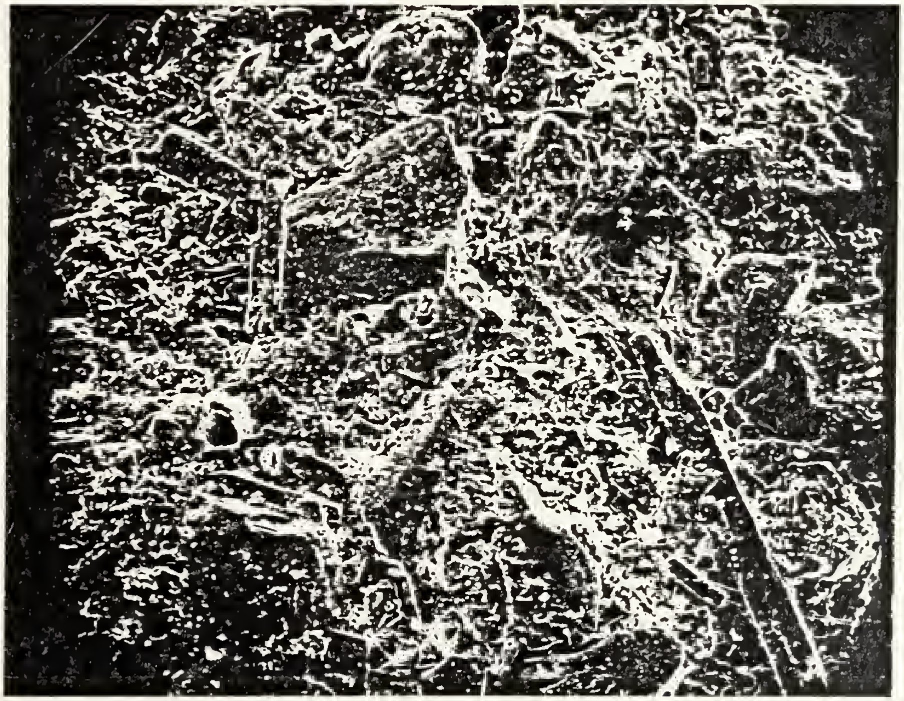


Figure 9 b OP 121 TT flux grain (X 200)

both fluxes were known to contain about 20% MgO the OP121TT was fused with an oxy-acetylene flame and then fractured. Mg was then observed in highly concentrated form in bands that can be clearly seen in the photographs [refer to figure 10A]. The 880 flux was much more uniform and Mg was easily detected without fusing.

The MnO contained in the OP121TT may be a major factor in the differences noted in the fracture toughness, although no obvious difference in microstructure was observed. The 0.2 % average difference in Mn is probably too small to significantly change the amount of acicular ferrite since it is still in a near optimum concentration in both sets of welds [22]. The slight increase may, however, be enough to improve consistency in the deposit Mn content, in another words, insuring enough Mn in spite of dilution or other variations due to the welding parameters. There is a clear reduction in the scatter of Charpy fracture energy when the OP121TT flux is used. This is evidenced by the fit of the regression model and the standard deviation of the Cv energy when taken on all the welds made with a particular flux.

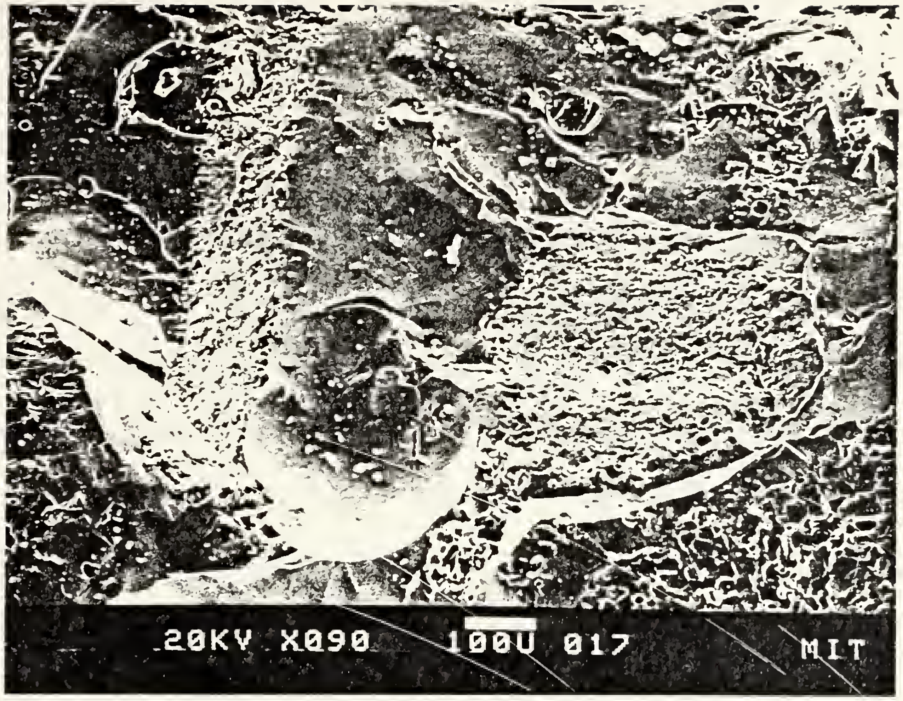


Figure 10 a Mg rich-bands in fused and fractured OP 121 TT (X 90)

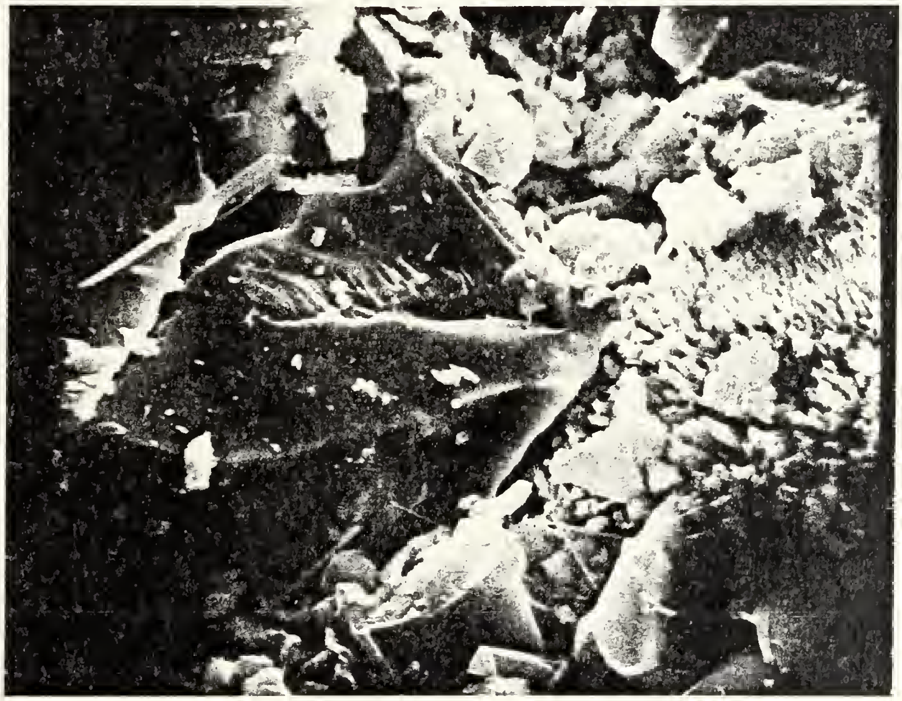


Figure 10 b Lincoln 880 flux grain showing fractured minerals and binder (X 5000)

4.6 HEAT INPUT

Heat input has already been noted as having little correlation with the fracture toughness. An examination of the iso Charpy energy plots [Appendix II] will reveal that both fluxes perform their best in the range of 2.0-2.4 KJ/mm (55-60 KJ/in). Heat input below this range will generally result in a deterioration in toughness more rapidly than higher heat input. If the peak Cv energies are 114 J and 119 J at 2.4 KJ/mm for the two fluxes and the extreme limits of heat input are used to set the values of voltage, current and travel speed, one may compare the ratios of change in Cv with change in heat. Though this comparison could be misleading it does show a greater loss per unit heat input when less heat input is used [refer to table 13].

TABLE 13 THE EFFECT OF HEAT INPUT VARIATIONS ON THE TOUGHNESS

	VOLTS	AMPS	TRVSPD in/min	HEAT INPUT KJ/mm	PREDICTED CV LINCOLN 880 Joules (ft lbs)	PREDICTED CV OP121TT Joules (ft lbs)
MINIMUM HEAT INPUT	30	400	18	1.58	87 (64)	96 (71)
OPTIMUM HEAT INPUT	31	575	18	2.4	114 (84)	119 (87)
MAXIMUM HEAT INPUT	36	600	12	4.25	91 (67)	68 (50)

The loss in Cv divided by the difference in heat input for the extremes shown above are

	LINCOLN 880	OP121TT
INCREASE IN HEAT	14.6 J/KJ/mm	12.4 J/KJ/mm
DECREASE IN HEAT	28.1	62.2

Clearly the decrease in heat input from the optimum is much worse for toughness than is the same increase above the optimum.

4.7 NON-METALLIC INCLUSIONS AND FRACTURE TOUGHNESS

Examination of the parent plate and the weld metal revealed many non-metallic inclusions. In the base plate the inclusion size varied between 0.2-2.0 microns. The distribution appeared uniform and the number of these inclusions was large compared to the relatively clean weld metal. The predominant material found in these inclusions was Mo followed by Mn, Al, Si, Ca and Cr in relative concentrations.

The generally small number of inclusions found in the weld metal were on the order of 10-15 microns [refer to figure 11]. The chemical analysis performed using EDAX detected Mn as the most common constituent. High relative Si and Al content was also typical with Ca, Ti, and Mg occasionally found. In the weld metal made with 880, Zr was also present in many of the inclusions. Except for the Zr, the weld metal produced with OP121TT contained the same type and size of inclusions. No correlation was observed between inclusion quantity and the toughness. This is explained by the low temperature used in the fracture test. The predominant mode of fracture is clevage in this case. The photographs of the fracture surface do show a clear increase in clevage on the main body of the break compared to the ductile tearing or micro void coalescence found on the shear lip [refer to figure 12, 13]. The fracture surface is not completely crystaline. There is an obvious ductile

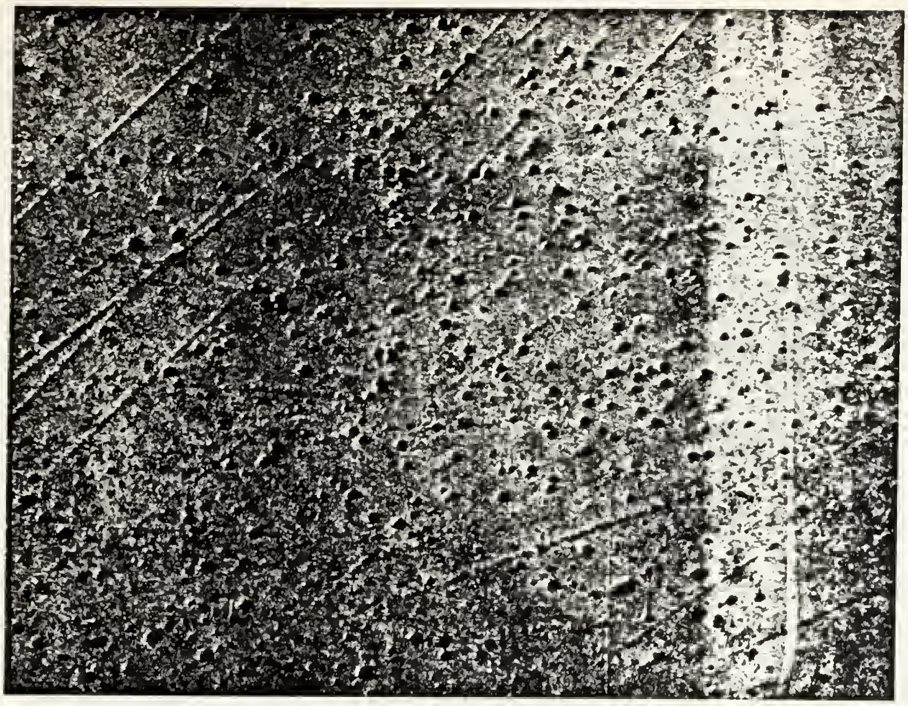


Figure 11 a Weld metal inclusions
(X 25) Lincoln 880-Cv 85 J

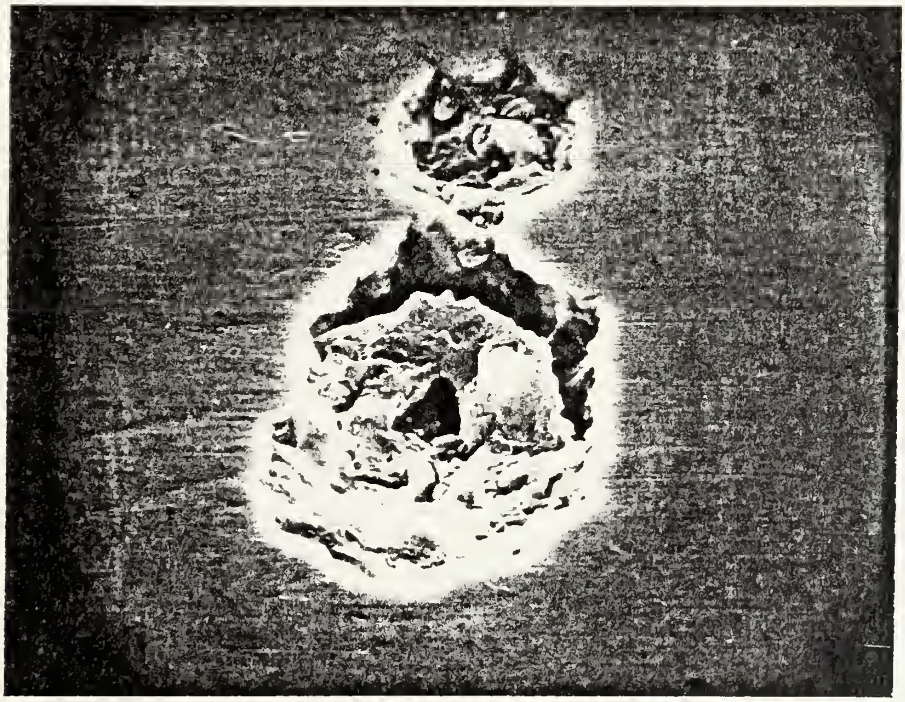


Figure 11 b Weld metal inclusion
(X 4600)

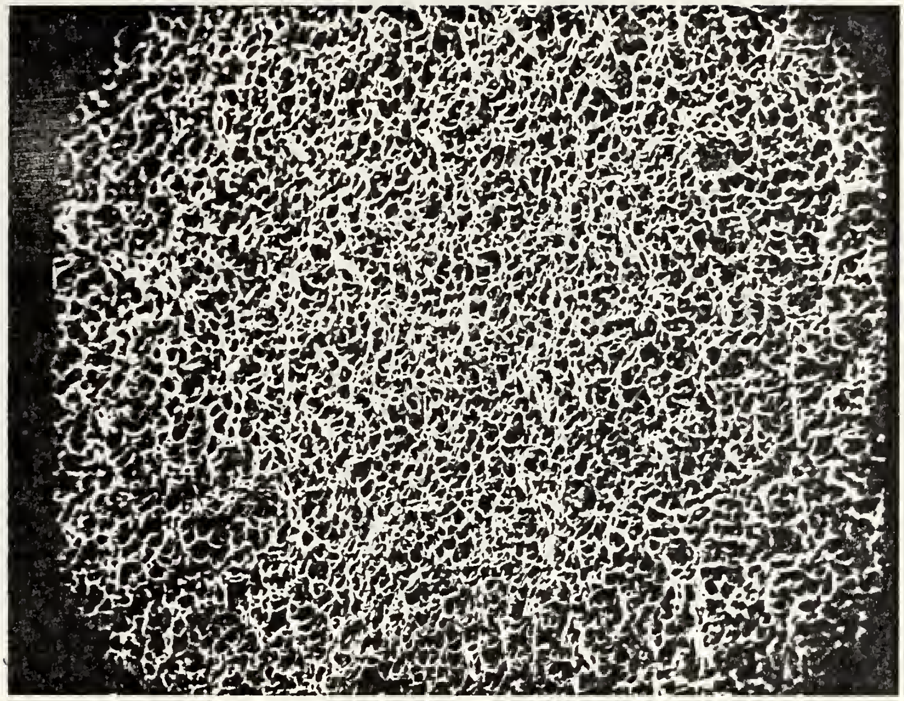


Figure 12 a Shear lip showing micro void coalescence (X 500)/ Cv 65 J

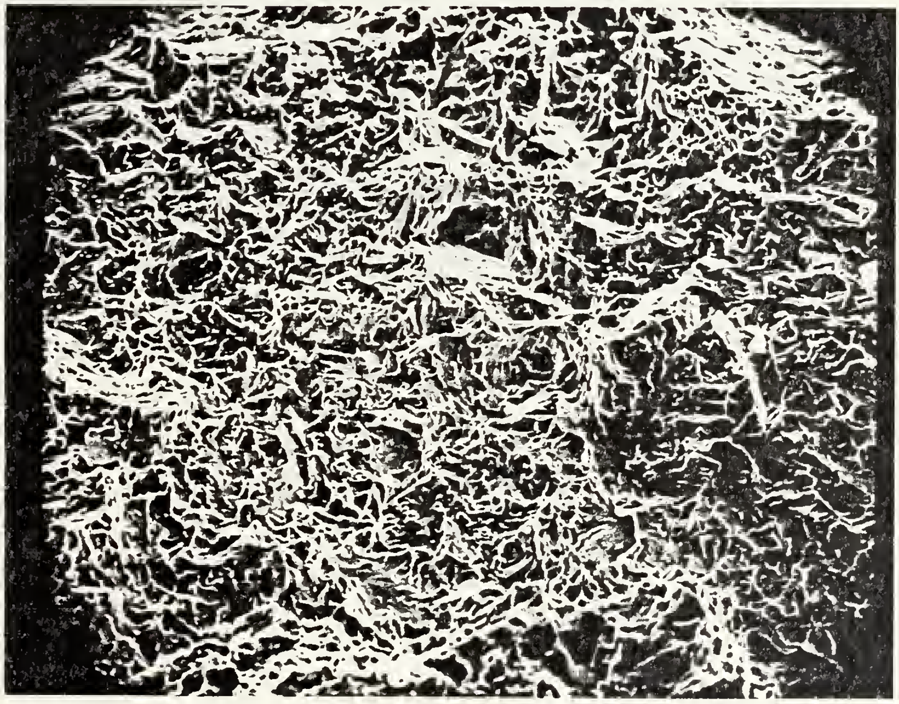


Figure 12 b Brittle fracture surface of the same specimen in 12 a. (X 500)

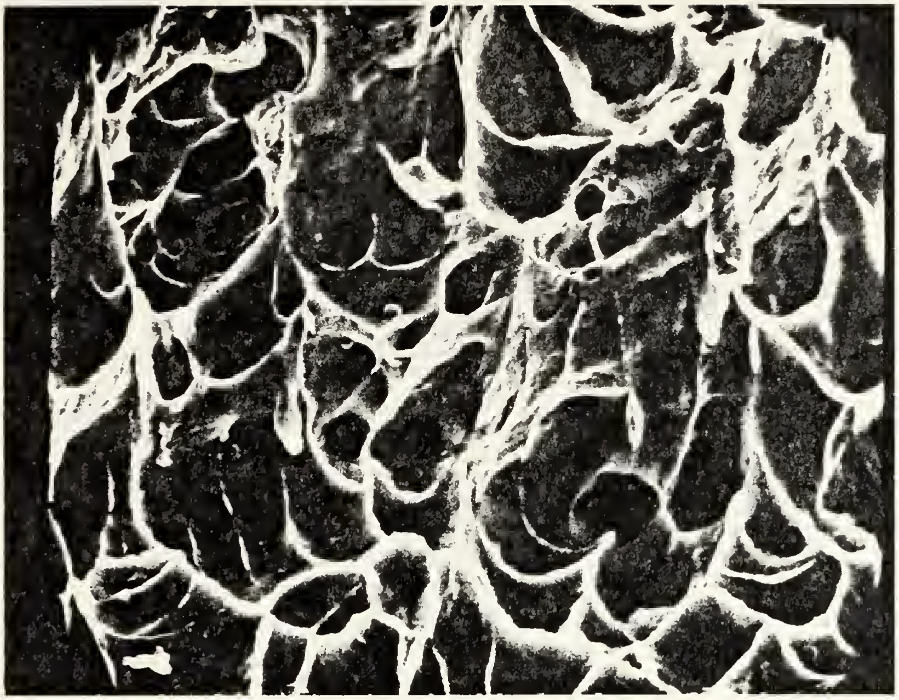


Figure 13 a Micro void coalescence on shear lip (X 5000)/Cv 126 J

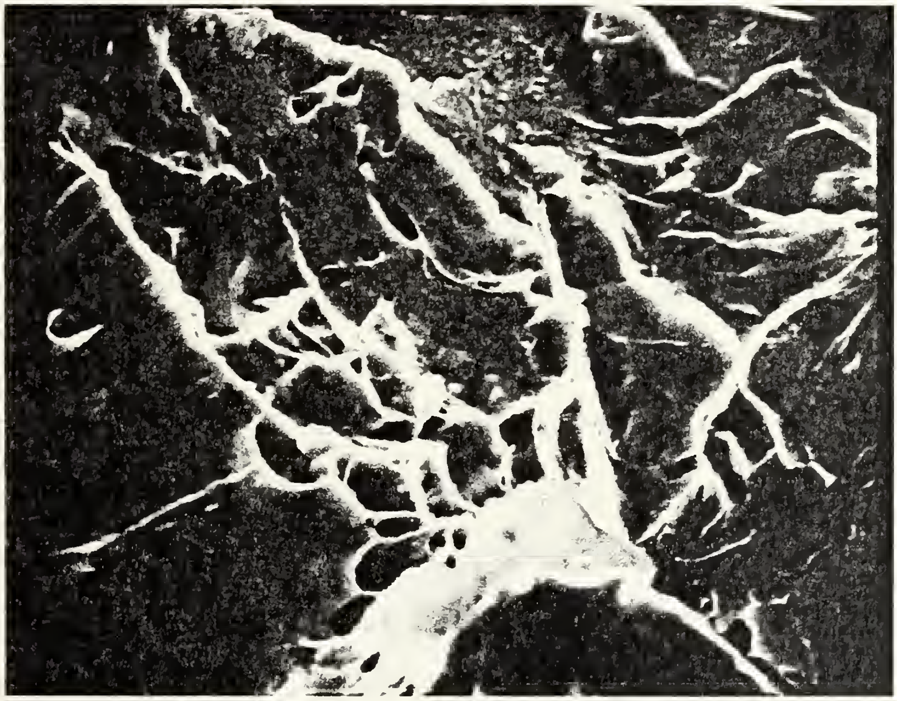


Figure 13 b Brittle fracture surface of the same specimen in 13 a. (X 5000)

behavior as well. The fracture energy is not substantially greater, however. The Cv energies for the two specimens are 65 J and 126 J, (figures 12 and 13 respectively). The size of the majority of the inclusions is much smaller than the micro voids and the large inclusions are simply too few in number to influence the fracture path.

4.8 MICROSTRUCTURE

Microscopic examination of the weld metal did not reveal significant differences. All of the welds consisted predominantly of a fine grained structure. This could be identified as acicular ferrite with some aligned structure that Abson and Dolby [29] call MAC (Martensite And Carbide) [refer to figure 14]. This assesment remains qualitative due to the small number of samples actually etched. A few samples were etched and observed under the electron microscope revealing two distinct structures [refer to figures 15, 16]. Of the samples examined only two welded with Lincoln 880 produced the smooth form seen in figure 15. This does necessarily confirm that the flux was responsible in view of the small sampling. The appearance is suggestive of over etching but intentional over etching of some other specimens did not produce this structure and only increased the angularity. If not caused by over etching it is likely that the explanation is transformation related. The toughness is not an issue since the same structure was found for both high and low fracture energies.

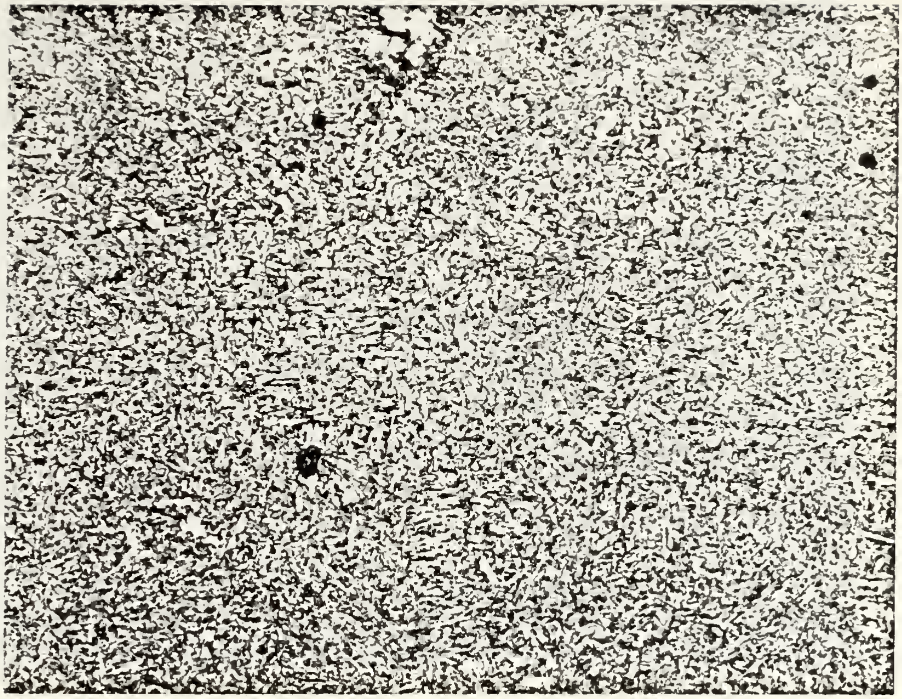


Figure 14 a Weld metal acicular ferrite
(X 250) 1% nital

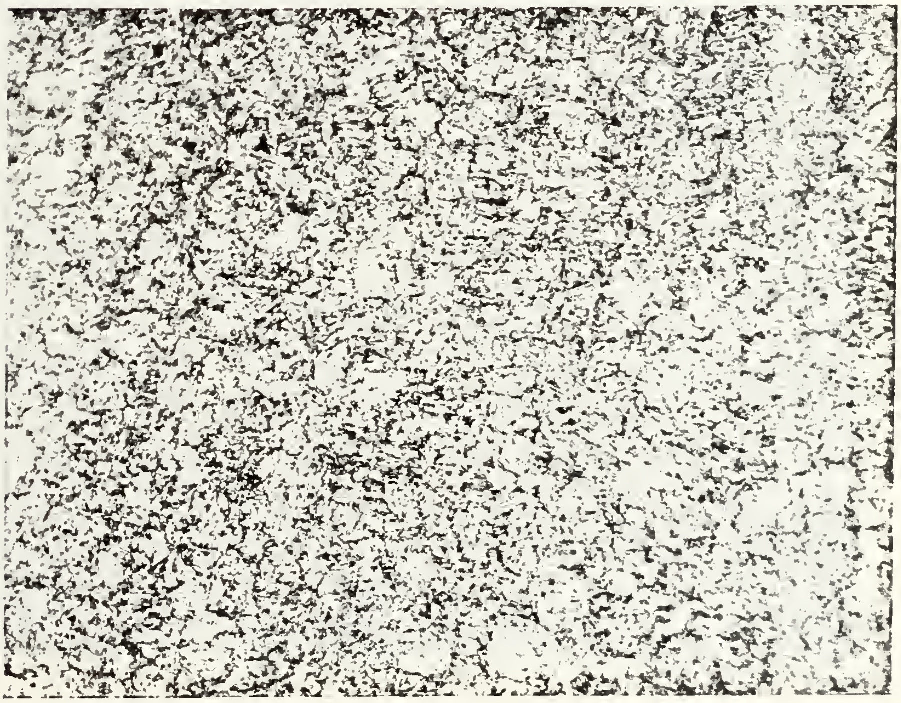


Figure 14 b HY-80 base plate microstructure
(X 250) 1% nital

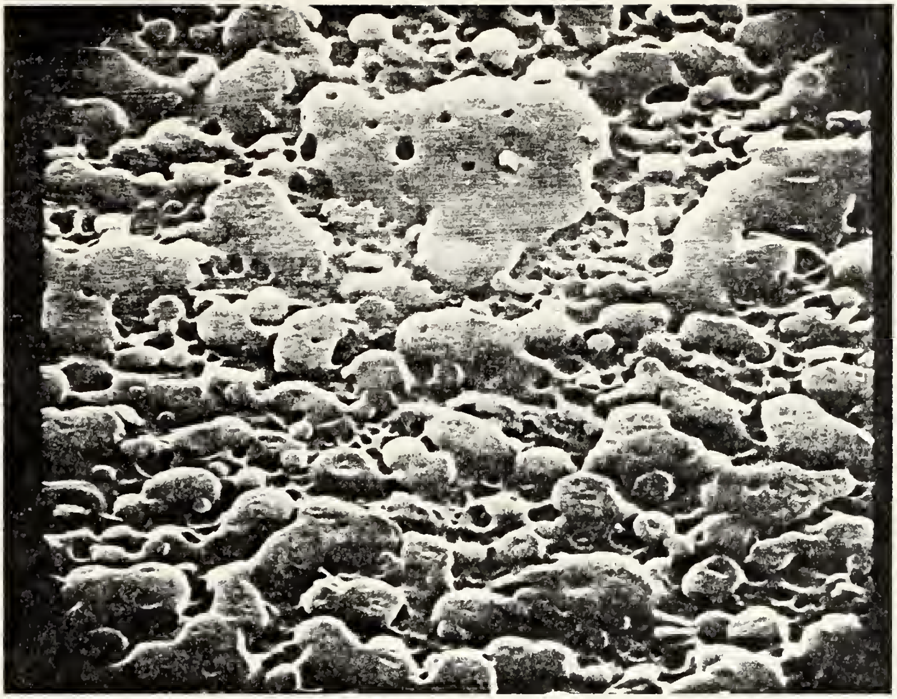


Figure 15 Microstructure of weld 4
1 % nital (X 5000)

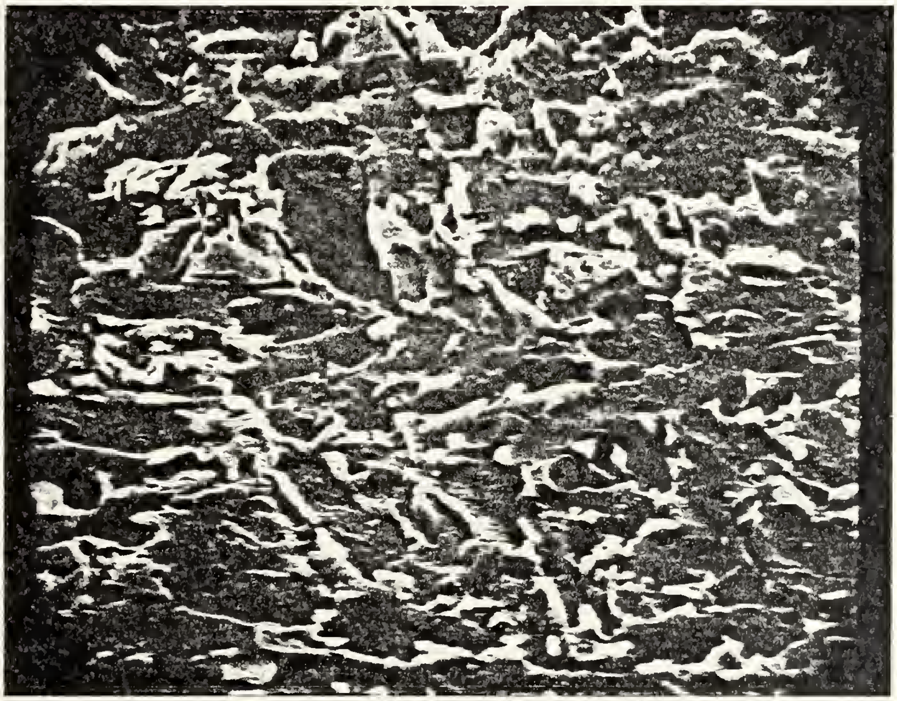


Figure 16 Microstructure of weld 28
1 % nital (X 5000)

5. CONCLUSIONS

The influence of the submerged arc welding parameters; voltage, current and travel speed on weld metal toughness has been studied. The following conclusions can be drawn from the investigations:

1. Voltage, current and travel speed variations play a significant role in the toughness of the weld metal.

2. Mn lost in the welding arc can be reduced or eliminated if the flux contains MnO.

3. The welding variables control the time available for chemical reactions to occur and can greatly influence the attainment of equilibrium in the slag, weld pool arc plasma system. This control is explained to a large extent by the dependence of arc length on voltage. The voltage drop across the arc will be reduced when higher electrode feed rates are employed.

4. The heat input does not uniquely control the weld metal toughness but heat input below 2 KJ/mm is more detrimental than is heat input above this level.

5. The weld metal made under OP121TT which contains 2 % MnO has a more consistent toughness and is less sensitive to current variations than is that formed when using Lincoln 880. Lincoln 880 has no MnO in its formulation.

6. Non-metallic inclusions found in the welds made with Lincoln 880 and OP121TT do not significantly affect the toughness in the brittle to ductile transition region.

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APPENDICES

APPENDIX I	CONTAINS ADDITIONAL COPIES OF THE IMPORTANT TABLES FOR REFERENCE
APPENDIX II	CONTAINS A COMPLETE SET OF ISO CHARPY PLOTS FOR WELDS MADE WITH LINCOLN 880 AND OP121TT FLUXES

TABLE 1

LIMITS OF LADLE and CHECK CHEMISTRY FOR HY-80

	WT PERCENT LADLE	WT PERCENT CHECK
CARBON	.12-.18	.10-.20
MANGANESE	.10-.40	.10-.45
PHOSPHORUS	.025 max	SAME AS LADLE
SULPHUR	.025 max	SAME AS LADLE
SILICON	.15-.35	.12-.38
NICKEL	2.00-3.25	1.93-3.32
CHROMIUM	1.00-1.80	0.94-1.86
MOLYBDENUM	.20-.60	0.17-0.63
TITANIUM	.02 max	
VANADIUM	.03 max	
COPPER	.25 max	

Note S + P must be less than .040 wt percent in both the ladle and check analyses

(Taken from MIL-S-16216H)

TABLE 2

BASE PLATE AND ELECTRODE COMPOSITION

	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al	Ti
AX-90 ELECTRODE 2.38 mm	.050	.46	1.31	.016	.007	.066	1.93	.41	.058	.003	.012	.013
HY-80 BASE PLATE	.16	.22	0.26	.012	.011	1.35	2.17	.23	.126	.004	.011	.002

TABLE 4 WELD DATA FOR LINCOLN 880

TEST	VOLTS	AMPS	TRSP in/min	HEAT KJ/in	CV* ftlb	DILUTION(Cr) % Base plate
2	33	500	15	66.0	45 84 34	20
3	30	500	12	75.0	50 50 46	31
4	30	500	18	50.0	83 93 80	17
5	33	400	12	66.0	37 47 32	21
6	33	400	18	44.0	62 63 43	14
7	33	600	12	99.0	76 76 71	31
8	33	600	18	66.0	78 96 77	23
9	36	500	12	90.0	43 46 43	28
10	36	500	18	60.0	42 58 39	28
11	33	500	15	66.0	76 91 66	21
12	36	600	15	86.4	79 83 61	39
13	30	400	15	48.0	48 50 38	15
14	30	600	15	72.0	62 77 54	39
15	33	500	15	66.0	80 99 65	25
16	36	400	15	57.6	54 55 36	27

*First value listed was from the Charpy specimen which was chemically analysed. The remaining two are CV energies of additional specimens from the same weld.

TABLE 5   WELD DATA FOR   OP 121 TT

TEST	VOLT	AMPS	TVSP in/min	HEAT KJ/in	CV* ftlb	% DILUTION(Cr) Base plate
17	33	500	15	66.0	71 75 68	23
18	30	500	12	75.0	52 59 49	28
19	33	400	12	66.0	48 48 46	19
20	33	400	18	44.0	64 81 64	32
21	33	600	12	99.0	46 51 44	25
22	33	600	18	66.0	72 64 79	27
23	36	500	12	90.0	60 69 50	30
24	36	500	18	60.0	71 73 67	17
25	33	500	15	66.0	86 88 66	29
26	36	600	15	86.4	61 65 60	35
27	30	400	15	48.0	52 58 41	18
28	30	600	15	72.0	75 85 74	42
29	36	400	15	57.6	51 57 41	18
30	33	500	15	66.0	57 64 53	36
31	30	500	18	50.0	89 93 85	22

*First value listed was from the Charpy specimen which was chemically analysed. The remaining two are Charpy energies of additional specimens from the same weld.

TABLE 6

EQUATIONS PREDICTING CHARPY VALUE BASED ON REGRESSION ANALYSIS USING THE SCALED VALUES OF VOLTAGE(V), CURRENT(I) AND TRAVEL SPEED(T)

$$CV\ (\text{ft lbs}) = X0 + X1(V) + X2(I) + X3(T) + X4(V\times I) + X5(V\times T) + X6(I\times T) + X7(V^2) + X8(I^2) + X9(T^2)$$

WHERE 30 TO 36 VOLTS IS SCALED TO -1 TO 1
400 TO 500 AMPERES IS SCALED TO -1 TO 1
12 TO 18 IN/MIN IS SCALED TO -1 TO 1

COEFFICIENT	LINCOLN 880	OP121TT
X0	71.1111	69.7778
X1	-3.8333	-3.6250
X2	13.5417	5.2083
X3	8.2083	11.6667
X4	1.7500	-3.8333
X5	-8.5833	-6.2500
X6	-2.0000	0.5833
X7	-10.0556	-.3056
X8	-2.9722	-9.4722
X9	-4.9722	-1.3889
R-SQUARED	56.3%	68.8%
PURE ERROR	34.7%	24.6%
LACK OF FIT	9.0%	6.6%
STANDARD DEV OF PREDICTION (FT LBS)	13.88	8.72

TABLE 6 A

	LINCOLN 880	OP121TT
R-SQUARED	56.3%	68.8%
VARIABLE	% OF R-SQUARED	% OF R-SQUARED
VOLTAGE	4.1%	5.4%
CURRENT	50.6%	11.1%
TRAVEL SPD	18.6%	55.5%
VOLTSxAMPS	0.4%	3.0%
VOLTSxTRAV SPD	10.2%	8.0%
AMPSxTRAV SPD	0.6%	0.1%
VOLTS SQUARED	11.6%	NIL
AMPS SQUARED	0.9%	16.6%
TRAV SPD SQUARED	3.2%	0.4%

The percentages in each column reflect the importance of the terms used in the regression to predict the toughness assuming all the terms are independant.

TABLE 7 WELD COMPOSITION DATA WITH LINCOLN 880

TEST	VOLT	AMPS	TVSP *	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	O
2	33	500	15	.047	.47	.89	.013	.005	.32	2.05	.41	.063	.018	.031
3	30	500	12	.054	.45	.80	.012	.006	.47	2.06	.39	.065	.019	.038
4	30	500	18	.068	.45	.92	.010	.005	.29	2.02	.41	.055	.012	.036
5	33	400	12	.077	.44	.86	.010	.005	.33	2.00	.41	.061	.009	.028
6	33	400	18	.068	.46	.90	.010	.004	.25	1.97	.42	.056	.015	.035
7	33	600	12	.087	.40	.84	.008	.005	.47	1.99	.38	.065	.010	.029
8	33	600	18	.052	.47	.99	.012	.005	.36	2.06	.41	.064	.020	.036
9	36	500	12	.087	.40	.82	.009	.005	.42	2.01	.40	.068	.008	.029
10	36	500	18	.056	.46	.84	.011	.006	.43	2.08	.40	.066	.018	.030
11	33	500	15	.045	.47	.92	.013	.006	.33	2.06	.41	.063	.018	.041
12	36	600	15	.086	.40	.78	.010	.006	.57	2.05	.36	.090	.009	.006
13	30	400	15	.046	.48	.91	.015	.005	.26	2.06	.42	.062	.021	.039
14	30	600	15	.070	.44	.88	.011	.006	.57	2.08	.36	.063	.020	.044
15	33	500	15	.071	.46	.85	.012	.005	.39	2.05	.40	.082	.010	.039
16	36	400	15	.055	.44	.80	.014	.005	.41	2.09	.40	.068	.016	.039
MEAN VALUES				.065	.44	.87	.011	.005	.39	2.04	.40	.066	.015	.035
STANDARD DEV				.015	.03	.06	.002	.001	.10	0.04	.02	.009	.005	.005

* TRAVEL SPEED IN INCHES/MIN.
CHEMICAL COMPOSITIONS IN WEIGHT PERCENT

TABLE 8 WELD COMPOSITION DATA WITH OP121TT

TEST	VOLT	AMPS	TVSP	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	O
17	33	500	15	.053	.44	1.10	.015	.006	.36	2.04	.40	.068	.018	.034
18	30	500	12	.058	.44	1.03	.015	.006	.43	2.04	.39	.070	.017	.036
19	33	400	12	.044	.44	1.10	.017	.005	.31	1.97	.40	.065	.015	.041
20	33	400	18	.110	.31	0.90	.017	.005	.48	2.03	.37	.086	.008	.041
21	33	600	12	.110	.33	0.99	.017	.005	.39	2.02	.39	.084	.012	.040
22	36	600	18	.051	.43	1.02	.014	.005	.41	1.99	.39	.072	.021	.037
23	36	500	12	.051	.41	0.99	.016	.005	.45	2.00	.38	.074	.016	.031
24	36	500	18	.053	.35	1.11	.017	.010	.29	1.99	.40	.074	.010	.040
25	33	500	15	.047	.41	0.98	.015	.005	.44	1.98	.38	.075	.017	.035
26	36	600	15	.081	.38	0.91	.016	.005	.52	2.04	.36	.073	.009	.033
27	30	400	15	.049	.46	1.10	.015	.010	.30	1.99	.40	.059	.019	.050
28	30	600	15	.087	.38	0.84	.015	.006	.61	2.02	.35	.090	.009	.044
29	36	400	15	.045	.42	1.13	.016	.004	.30	1.99	.40	.083	.008	.041
30	33	500	15	.077	.39	0.93	.018	.005	.53	2.02	.36	.100	.010	.033
31	30	500	18	.045	.42	1.10	.017	.004	.35	1.99	.39	.086	.010	.050
MEAN VALUES				.064	.40	1.02	.016	.006	.41	2.01	.38	.077	.013	.039
STANDARD DEV.				.023	.04	0.09	.001	.002	.10	0.02	.02	.011	.005	.006

TRAVEL SPEED IN INCHES/MIN
CHEMICAL ANALYSIS IN WEIGHT PERCENT

TABLE 9 WELD DATA FOR LINCOLN 880

TEST	VOLT	AMPS	TVSP	CV*	NR. OF PASSES	APPROXIMATE ELECT.FD RATE	CALCULATED DILUTION (Cr)	(Ni)
2	33	500	15	45	13	130 in/min	.20	.50
3	30	500	12	50	7	120	.31	.55
4	30	500	18	83	13	130	.17	.38
5	33	400	12	37	11	90	.21	.29
6	33	400	18	62	21	85	.14	.18
7	33	600	12	76	7	175	.31	.25
8	33	600	18	78	13	175	.23	.55
9	36	500	12	43	7	120	.28	.34
10	36	500	18	42	11	120	.28	.63
11	33	500	15	76	11	130	.21	.55
12	36	600	15	79	7	160	.39	.50
13	30	400	15	48	14	100	.15	.55
14	30	600	15	62	9	190	.39	.63
15	33	500	15	80	11	130	.25	.50
16	36	400	15	54	16	100	.27	.67
MEAN VALUES				61			.26	.47
STANDARD DEV				16			.08	.15

DILUTION BASED ON THE MEASURED CHROMIUM AND NICKEL CONTENTS OF THE WELD METAL

$$\text{Dilution} = \frac{[\%M(\text{weld metal}) - \%M(\text{electrode})]}{[\%M(\text{base plate}) - \%M(\text{electrode})]}$$

Where M is Cr or Ni content

TABLE 10 WELD DATA FOR OP121TT

TEST	VOLT	AMPS	TVSP	CV*	NR. OF PASSES	APPROXIMATE ELECT.FD.RATE	CALCULATED DILUTION	
							(Cr)	(Ni)
17	33	500	15	71	10	130 in/min	.23	.46
18	30	500	12	52	7	120	.28	.46
19	33	400	12	48	10	90	.19	.17
20	33	400	18	64	18	85	.32	.42
21	33	600	12	46	7	175	.25	.38
22	36	600	18	72	9	175	.27	.25
23	36	500	12	60	9	120	.30	.29
24	36	500	18	71	15	120	.17	.25
25	33	500	15	86	11	130	.29	.21
26	36	600	15	61	9	160	.35	.46
27	30	400	15	52	15	100	.18	.25
28	30	600	15	75	9	190	.42	.38
29	36	400	15	51	15	100	.18	.25
30	33	500	15	57	11	130	.36	.38
31	30	500	18	89	13	130	.22	.25
MEAN VALUES				64			.27	.32
STANDARD DEV				13			.08	.10

DILUTION BASED ON THE MEASURED CHROMIUM AND NICKEL CONTENTS OF THE WELD METAL

$$\text{Dilution} = \frac{[\%M(\text{weld metal}) - \%M(\text{electrode})]}{[\%M(\text{base plate}) - \%M(\text{electrode})]}$$

Where M is Cr or Ni content

TABLE 11

REPORTED FLUX COMPOSITIONS

COMPOUND	LINCOLN 880 WT PERCENT		OP121TT WT PERCENT			
ANALYSIS	(A)	(B)	(C)	(D)	(E)	(F)
REFERENCE	[31]	[32]	[32]	[30]	[33]	[34]
SiO_2	16.0	13.9	15.6	13.5	13.4	15.0
MnO	NONE	NONE	1.9	1.8	0.9	? *
CaO	3.0	2.1	7.0	8.0	11.0	? *
MgO	27.0	26.3	25.7	43.6	40.0	? *
Al_2O_3	22.0	22.7	19.2	18.1	14.2	? *
TiO_2	2.0	NONE	1.1	1.0	0.5	? *
CaF_2	22.0	22.7	26.5	20.99	14.4	25.0
ZrO_2	4.0	7.4	NONE	0.2	NONE	NONE
FeO	NONE	1.0	NONE	NONE	1.7	NONE
Na_2O	NONE	2.0	NONE	NONE	0.9	NONE
K_2O	NONE	NONE	NONE	0.2	0.8	NONE
BaO	NONE	NONE	NONE	NONE	0.1	NONE

* $SiO_2 + TiO_2 = 15.0$

$CaO + MgO = 35.0$

$Al_2O_3 + MnO = 20.0$

The above analyses are from the literature and have in most cases been based on the assumption that all the elements are in an oxide form. This assumption therefore will not show the presence of the binding agent which is probably a potassium or sodium silicate. The actual form of the compounds is most likely much different, for example it is known that Lincoln 880 contains ZrO_2 as a zirconium silicate.

TABLE 12

COMPARISON OF CHARPY ENERGIES BASED ON VARIOUS SETS OF DATA

DATA BASE	NR. OF CHARPY BARS SAMPLED	MEAN CV FT LBS(-60F)	STANDARD DEV FT LBS	FLUX TYPE
MIT WELDS	45	61.5	18.73	LINCOLN 880
MIT WELDS	45	63.8	13.94	OP 121 TT
ELECTRIC BOAT	42	34.2	15.56	LINCOLN 880
ELECTRIC BOAT	40	64.0	12.26	OP 121 TT

WELDS MADE AT ELECTRIC BOAT WERE ACCOMPLISHED UNDER SIMILAR CONDITIONS WITH HEAT INPUTS 2.0 TO 4.3 KJ/MM. ELECTRODE STICKOUT FOR E.B. WAS 25 MM INSTEAD OF 19 MM

TABLE 14

LIST OF MATERIALS USED

1. HY-80 1 INCH PLATE (LUKENS STEEL CO.)
   MELT: C2724 SLAB:2BB [A]
2. HY-80 1 INCH x 0.5 INCH BACKING BAR
   MELT: C8583-83 [A]
3. AX-90 ELECTRODE (AIRCO)
   HEAT: 3P9530 01021A4A 3/32 INCH (2.38 mm) [B]
4. FLUX LINCOLN 880 LOT 65-Y [C]
5. FLUX OERLIKON OP121TT LOT 120004

[A] Made under MIL S-16216H

[B] Made under MIL E-23765/2

[C] Made under MIL E-18251C

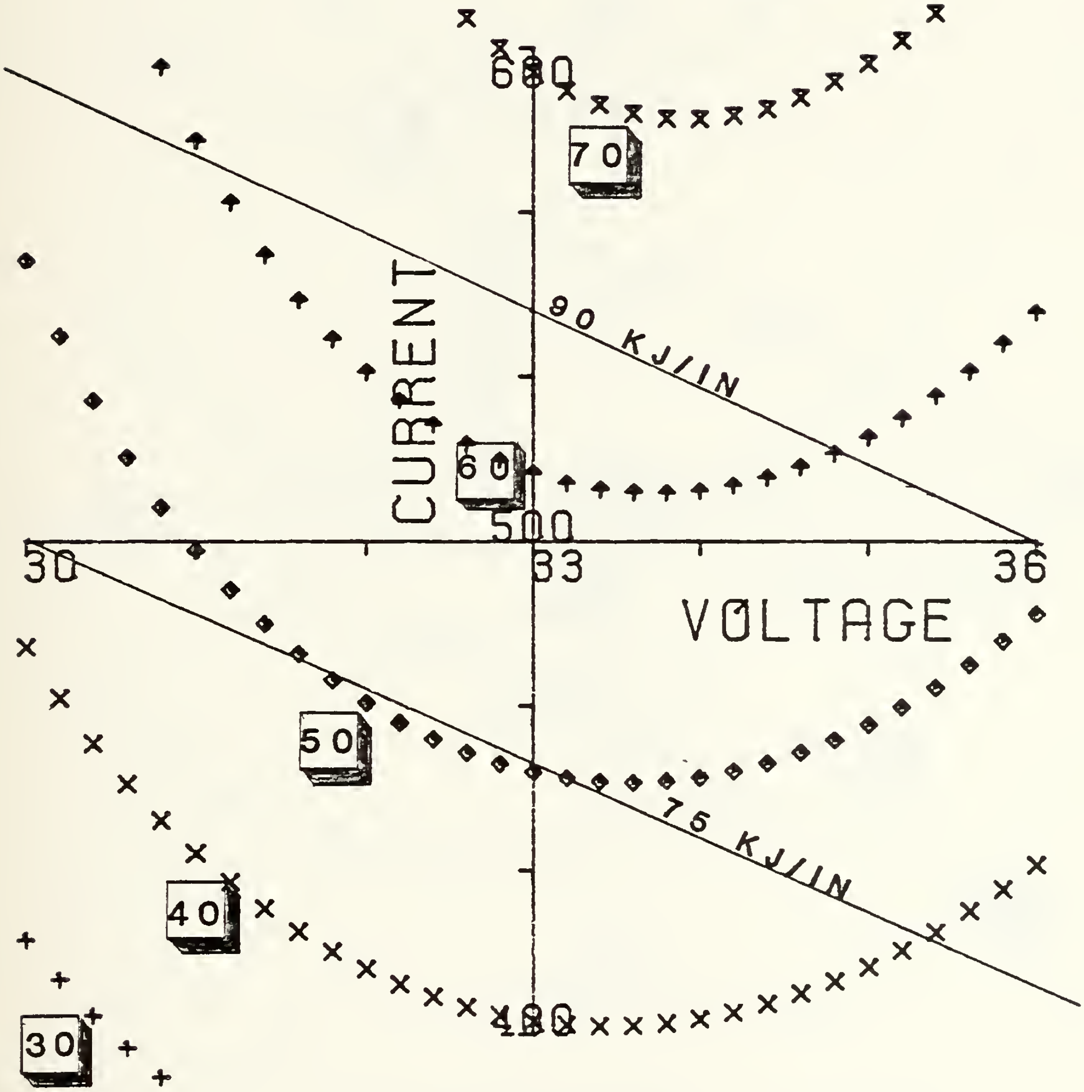
BASE PLATE DATA

YIELD	94,200 PSI	650 MPA
	92,900	641
ULT	107,600 PSI	742 MPA
	106,600	736
ELONGATION	20%	
REDUCTION IN	63.1%	
AREA	65.3%	
CHARPY ENERGY	110 ftlbs	149 J
AT -120 F	96	130 J
(-84 C)	92	125 J

The HY-80 plate used had been water quenched from 1650 F(900 C)
Tempering was done at 1220 F (660 C)

ISO CHARPY ENERGY

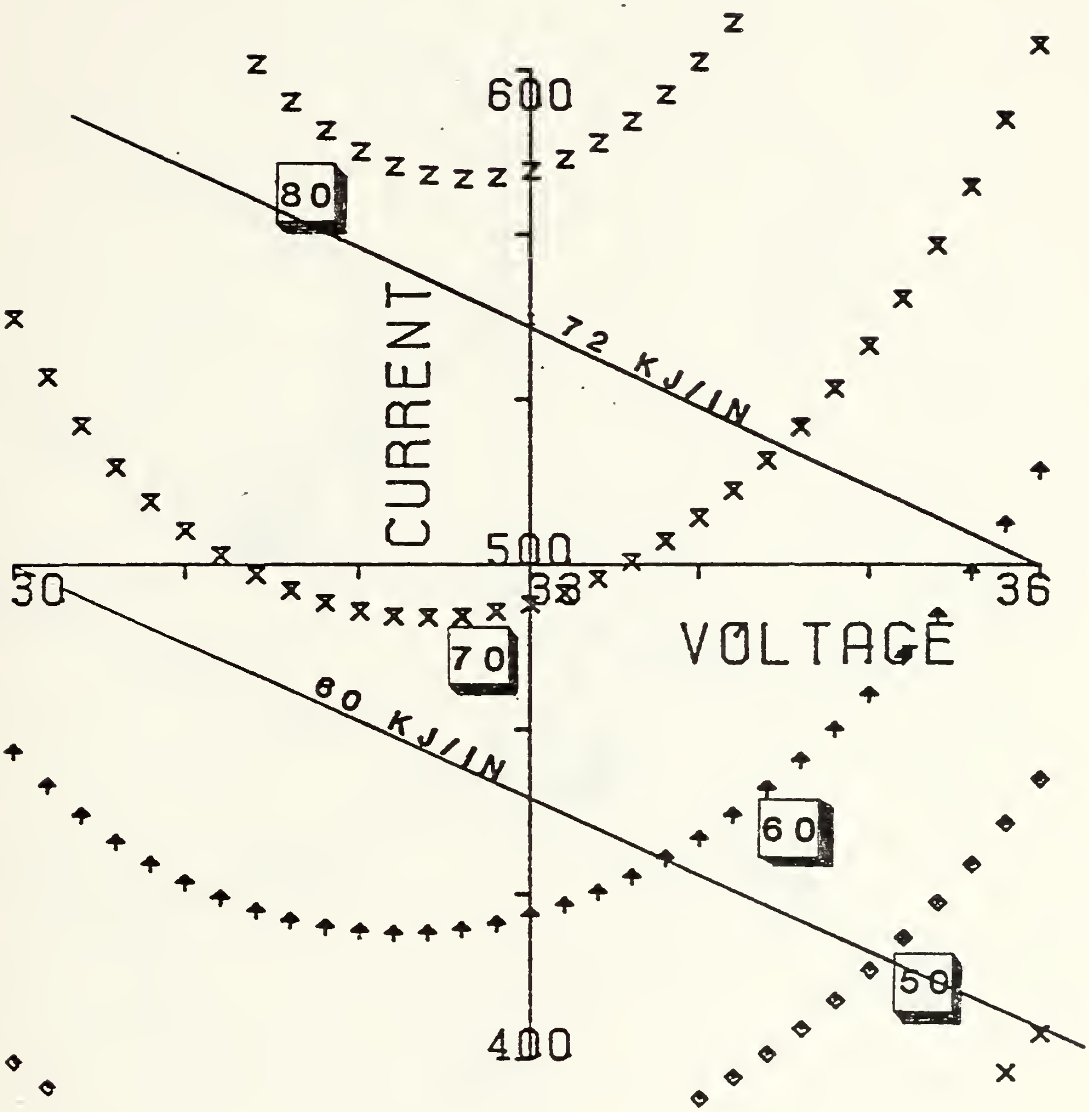
LINCOLN 880



TRAVEL SPEED 12 in/min
(FT-LBS)

ISO CHARPY ENERGY

LINCOLN 880

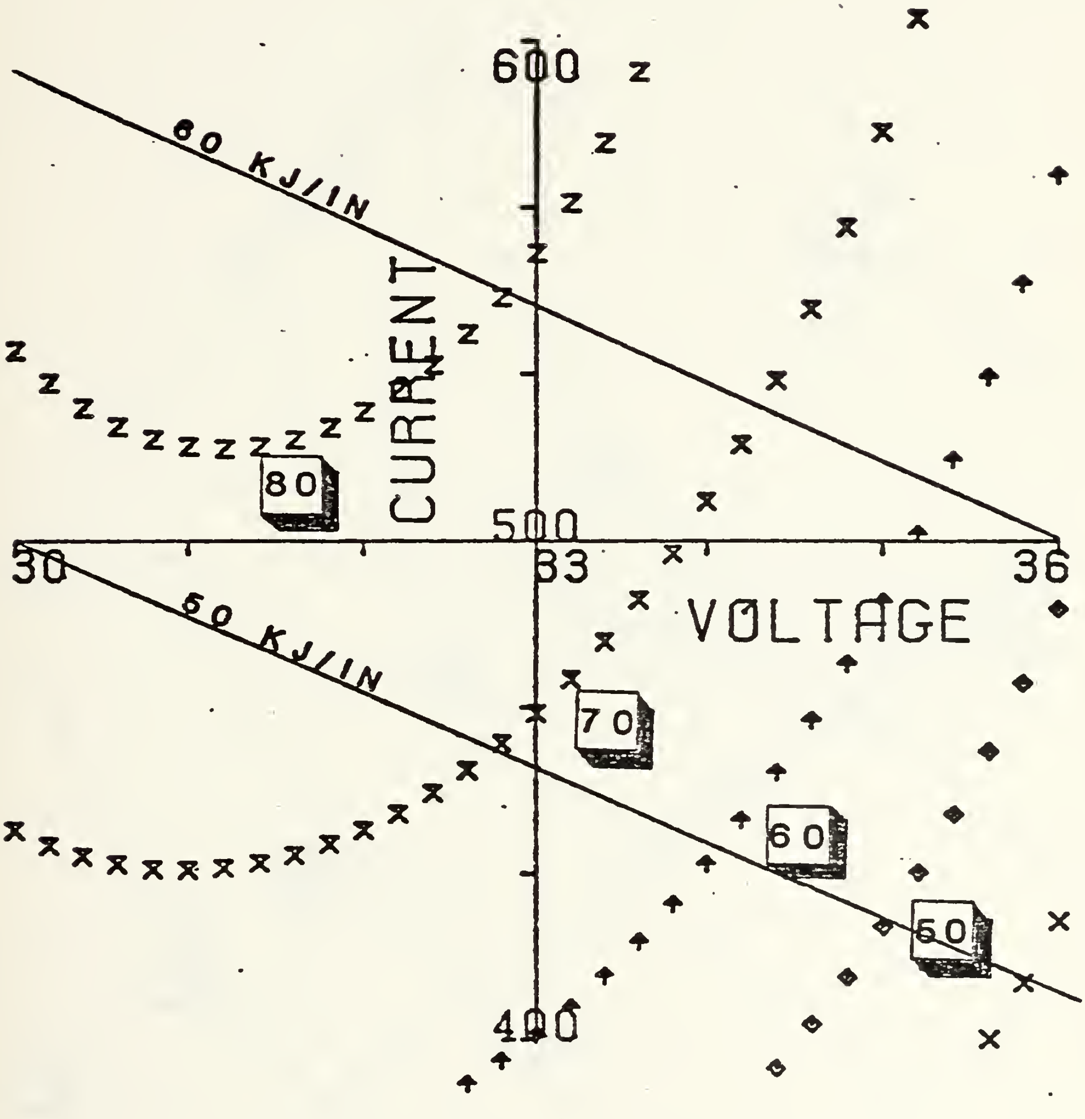


TRAVEL SPEED 15 in/min

(FT-LBS)

ISO CHARPY ENERGY

LINCOLN 880

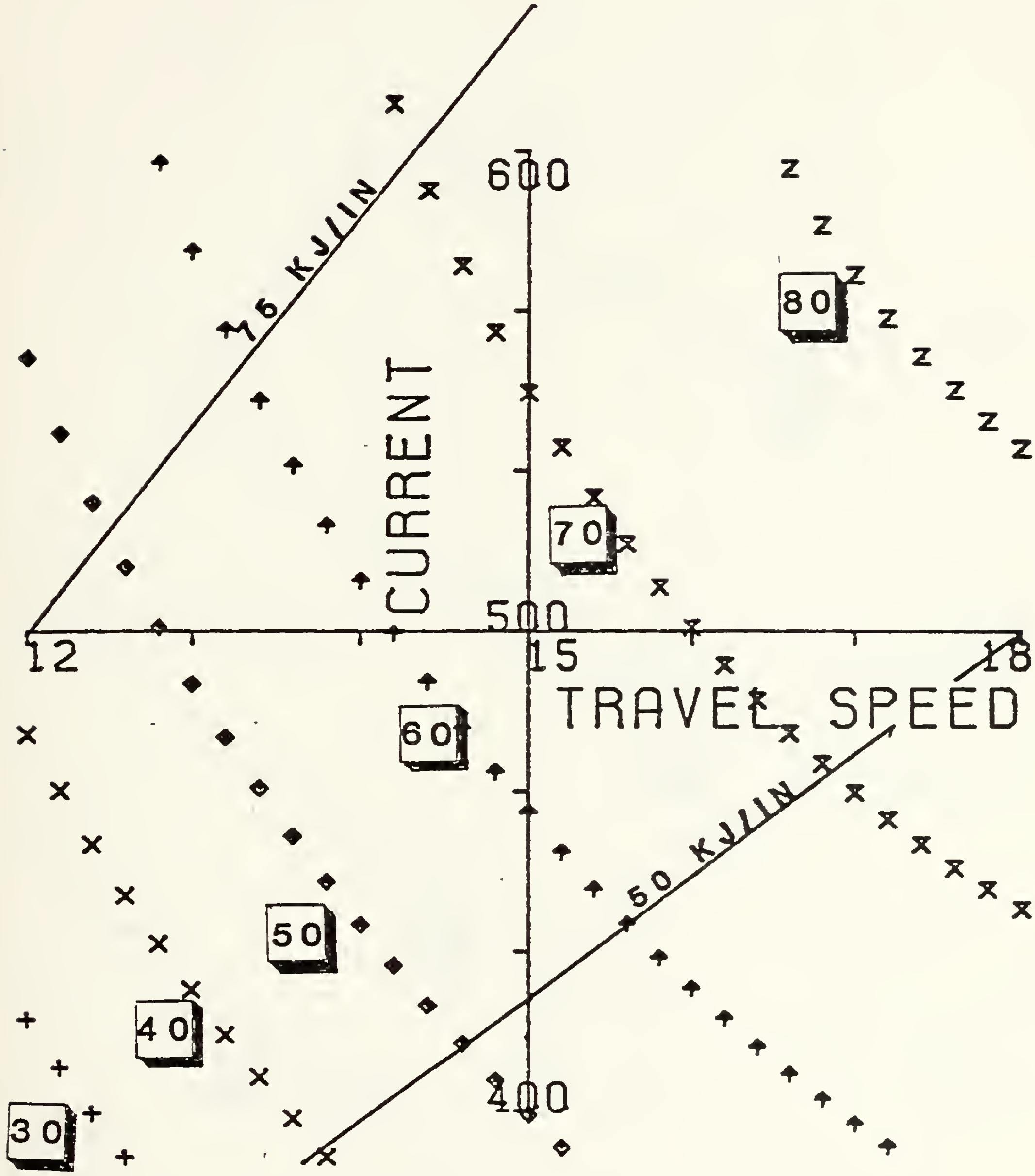


TRAVEL SPEED 18 in/min

Cv ENERGY IN FT-LBS

ISO CHARPY ENERGY

LINCOLN 880

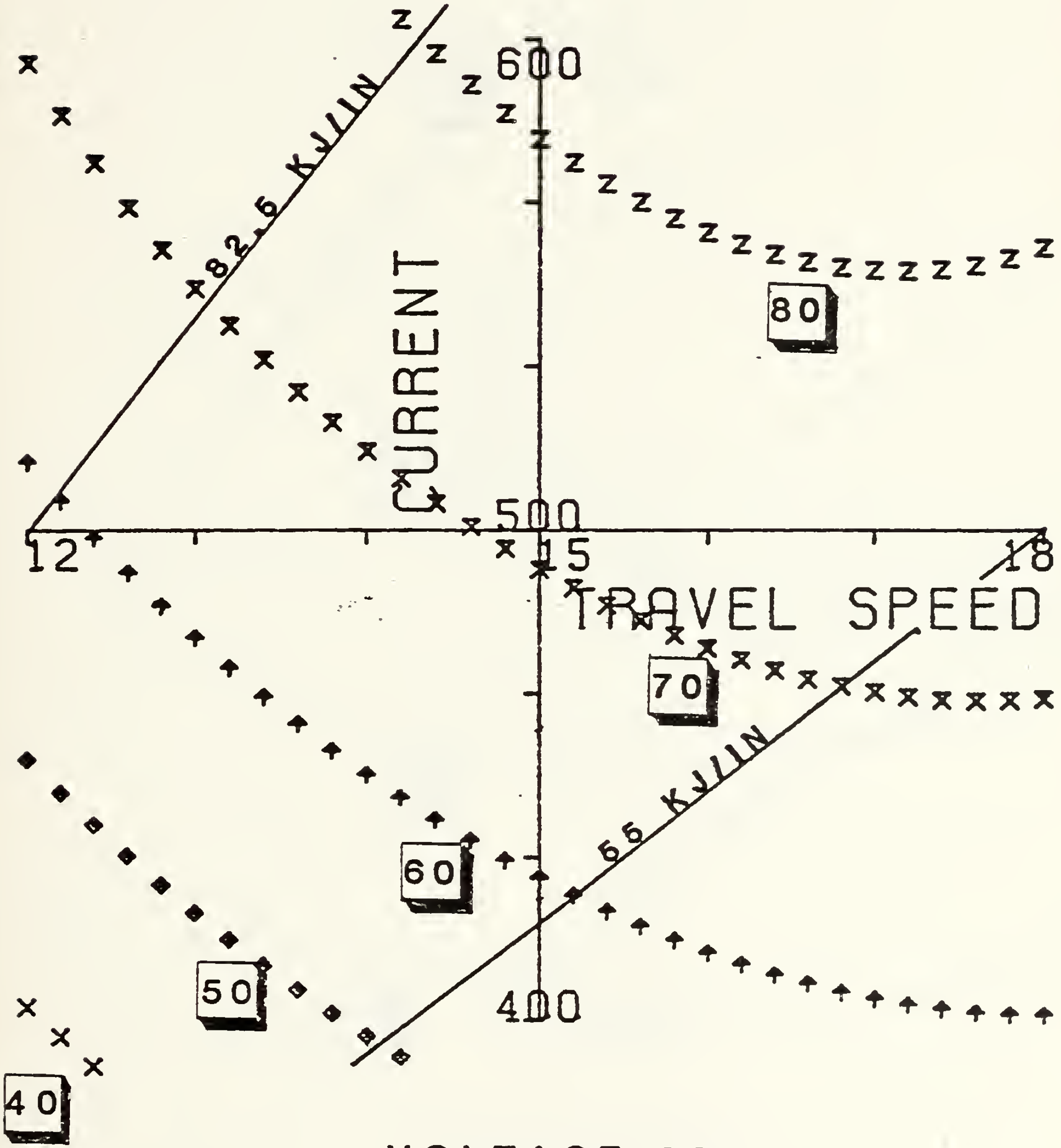


VOLTAGE 30

(FT-LBS)

ISO CHARPY ENERGY

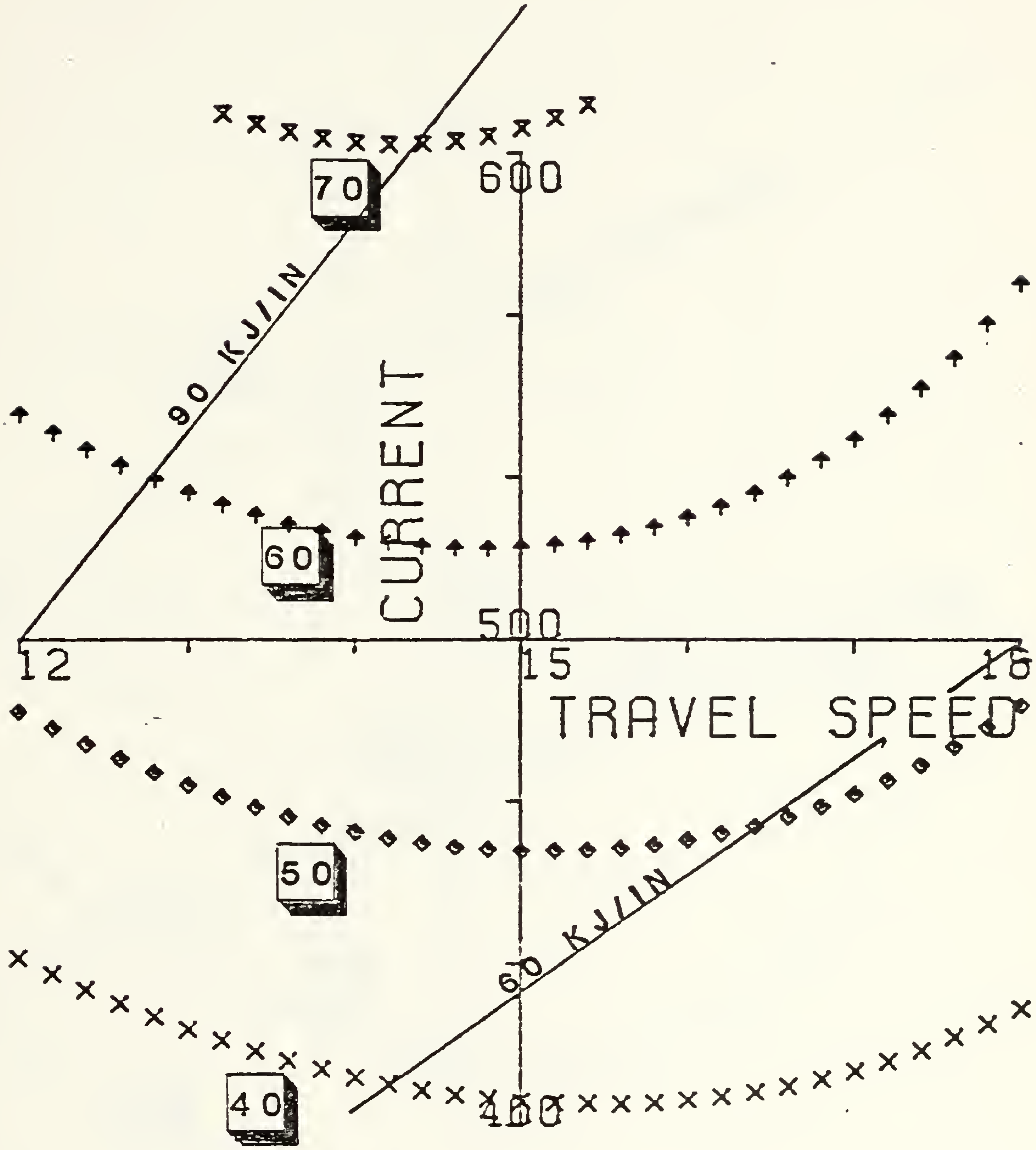
LINCOLN 880



VOLTAGE 33
(FT-LBS)

100 CHARPY ENERGY

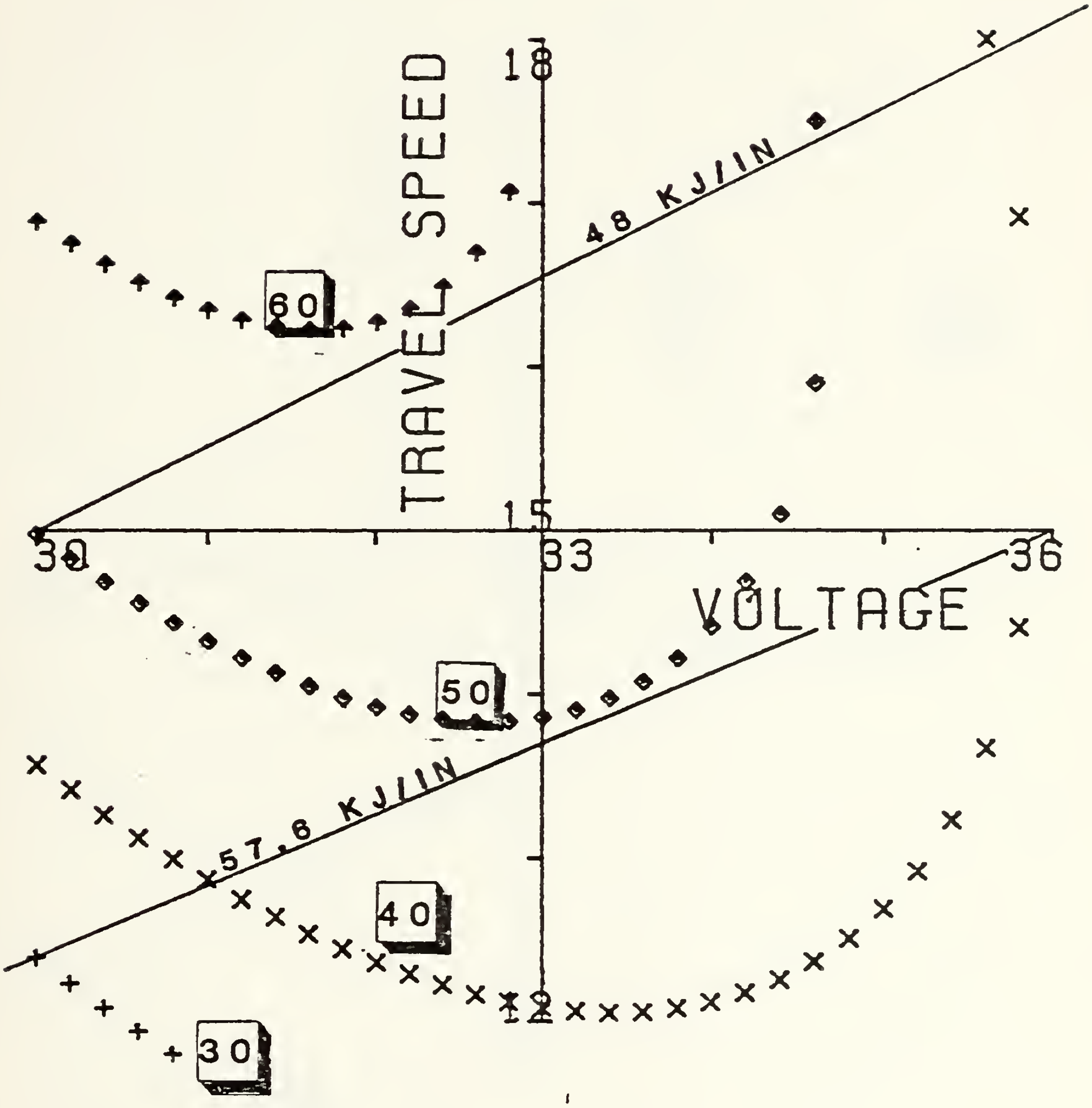
LINCOLN 880



VOLTAGE 36
(FT-LBS)

ISO CHARPY ENERGY

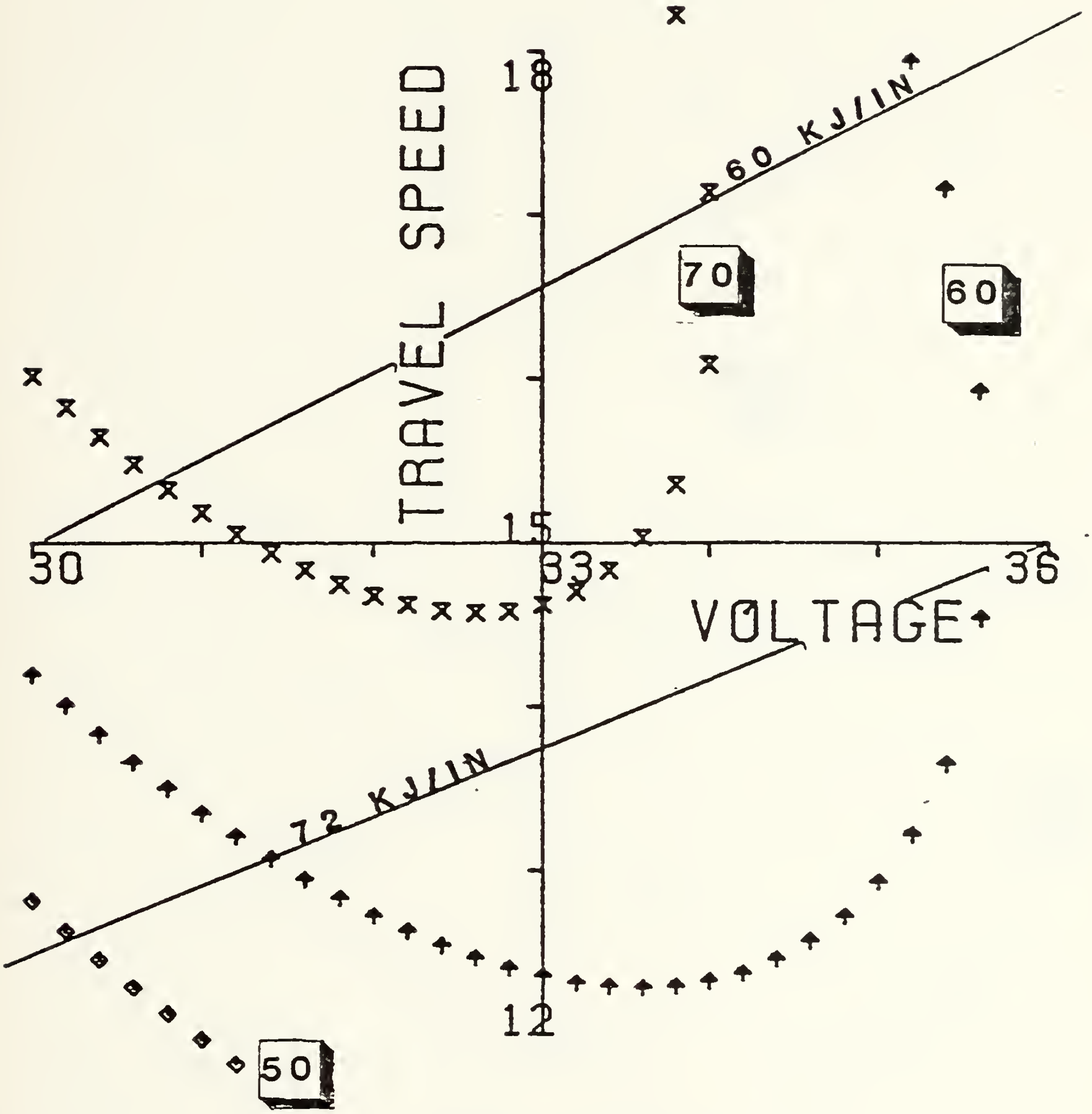
LINCOLN 880



AMPS 400
(FT-LBS)

ISO CHARPY ENERGY

LINCOLN 880

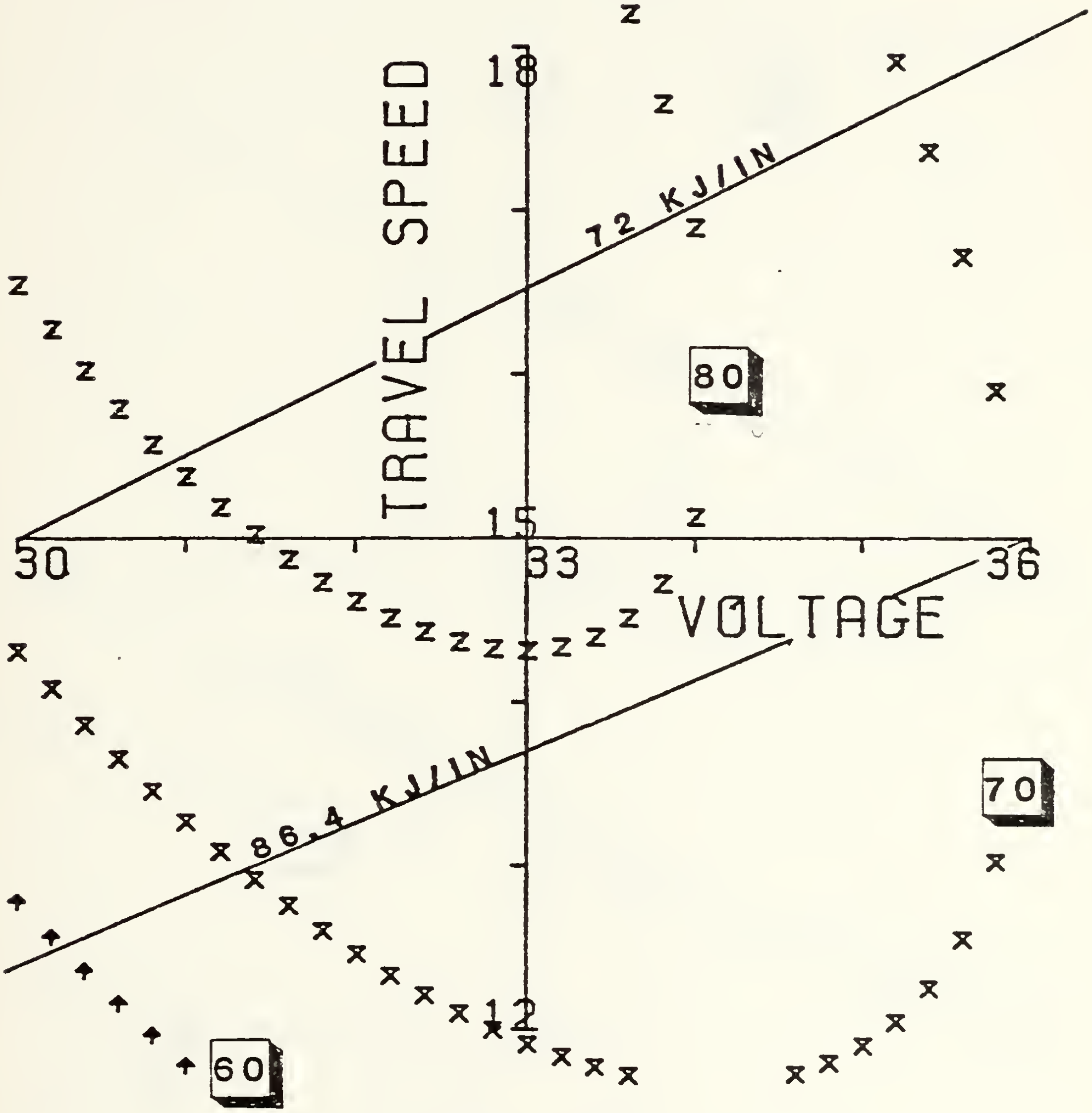


AMPS 500

(FT-LBS)

ISO CHARPY ENERGY

LINCOLN 880

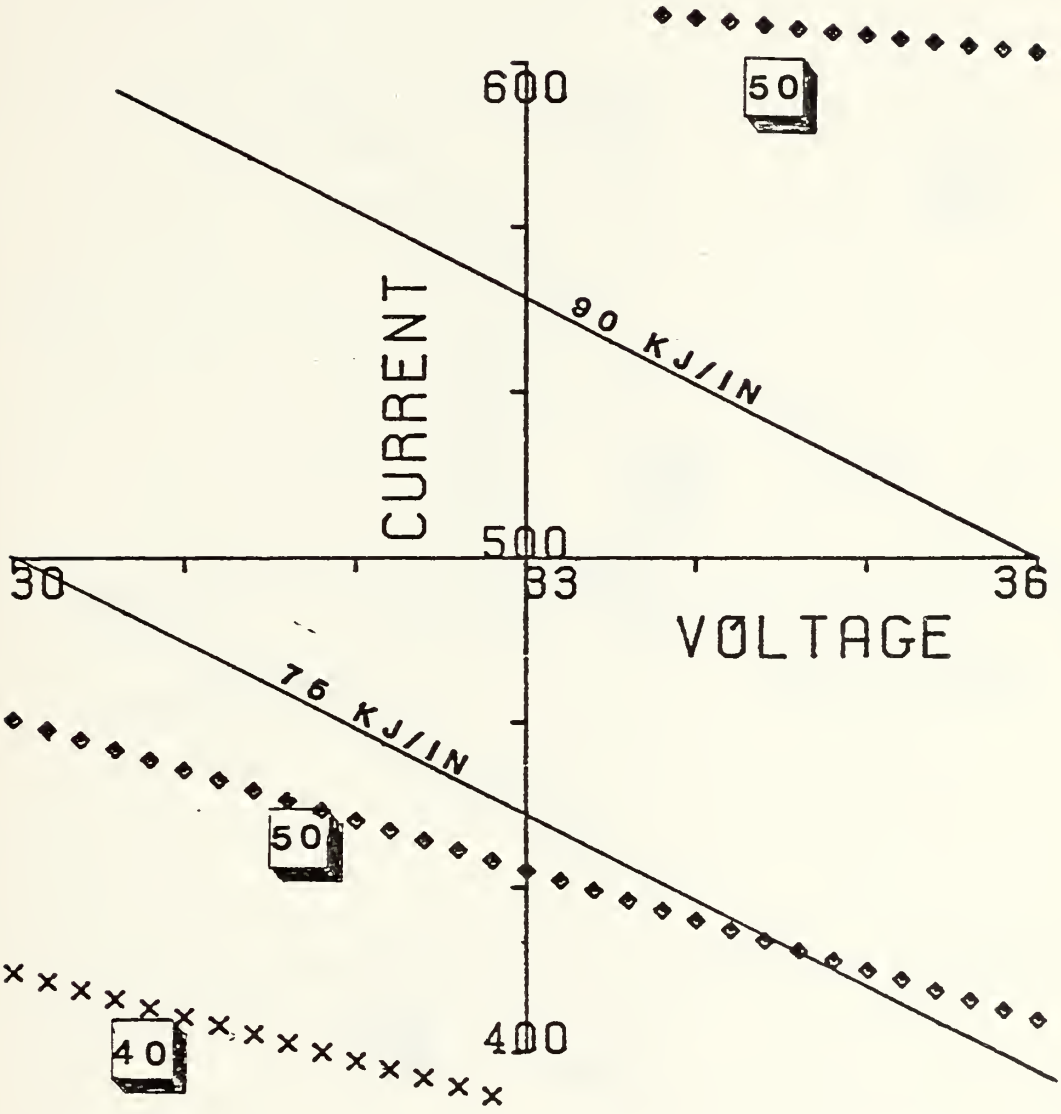


AMPS 600

(FT-LBS)

ISO CHARPY ENERGY

OP 121 TT

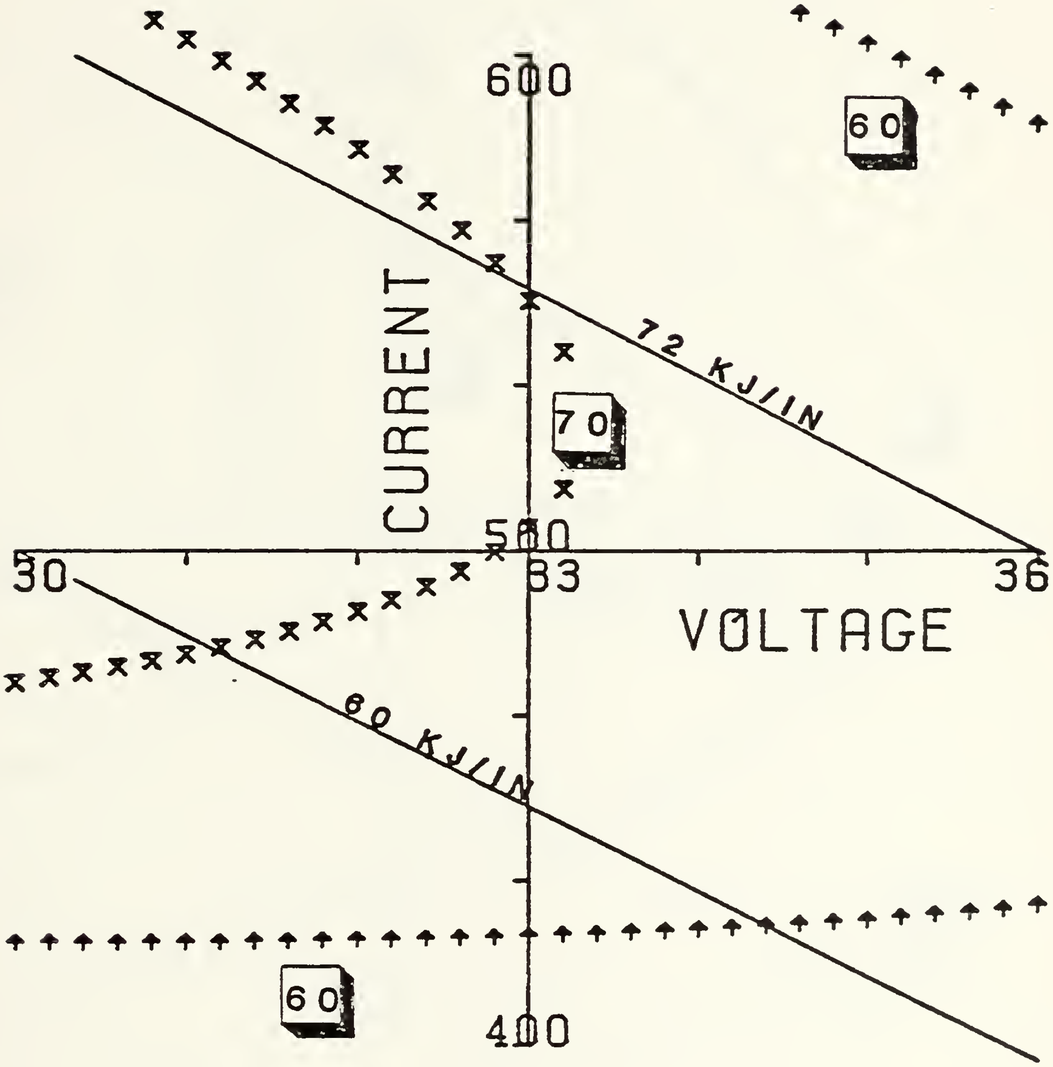


TRAVEL SPEED 12 in/min

(FT-LBS)

ISO CHARPY ENERGY

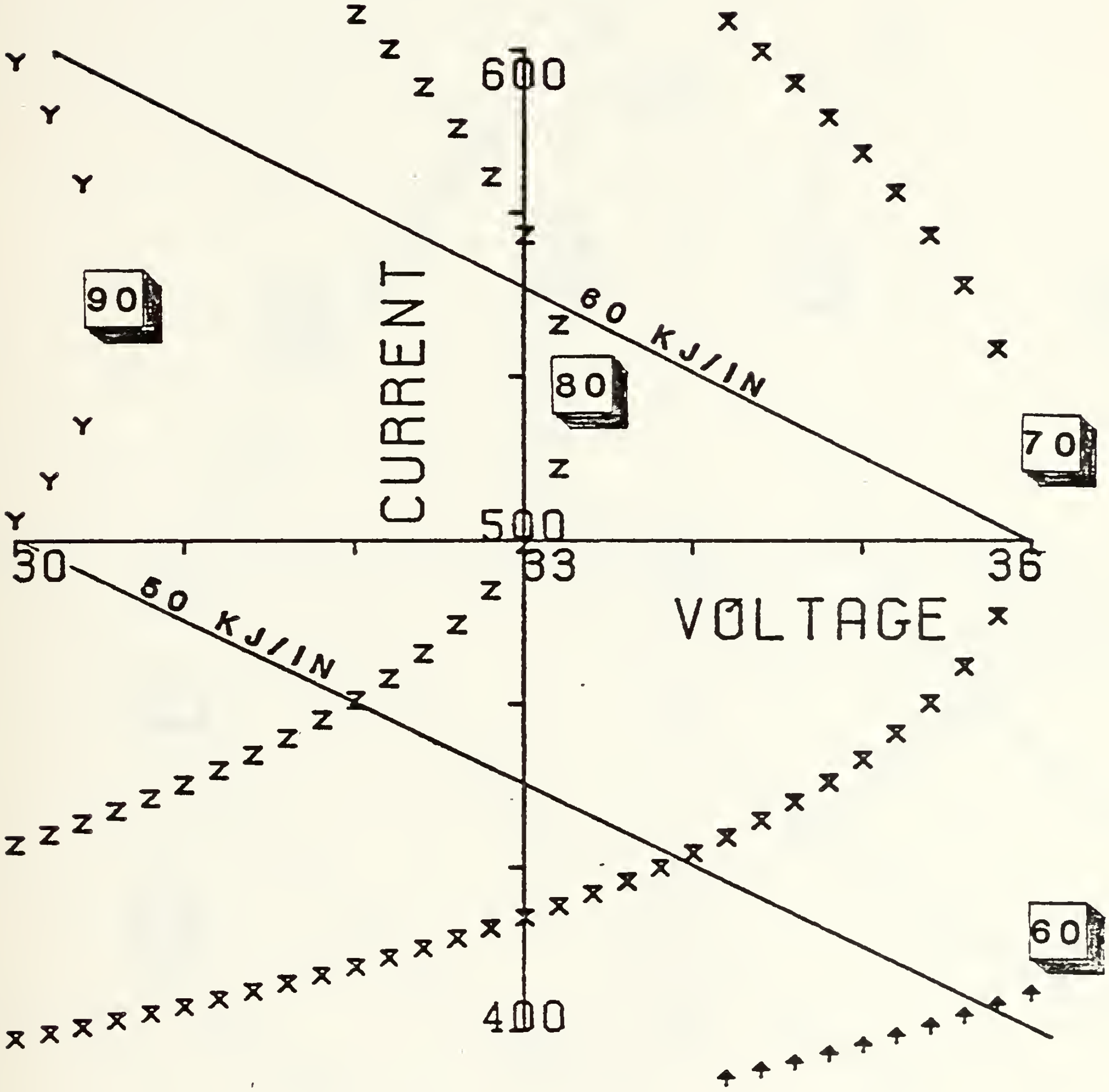
OP 121 TT



TRAVEL SPEED 15 in/min
(FT-LBS)

ISO CHARPY ENERGY

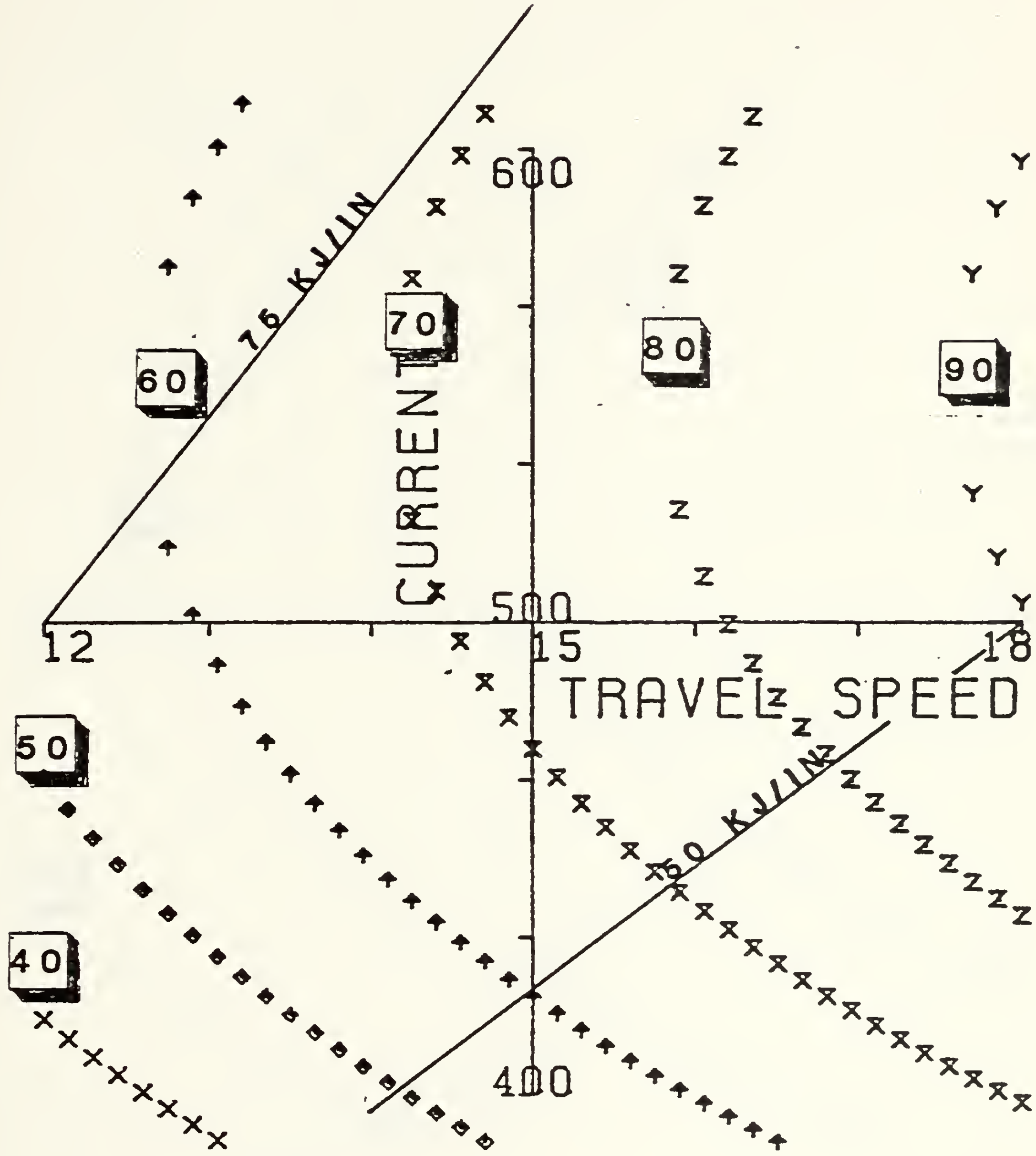
OP 121 TT



TRAVEL SPEED 18 in/min
Cv ENERGY IN FT-LBS

ISO CHARPY ENERGY

OP 121 TT

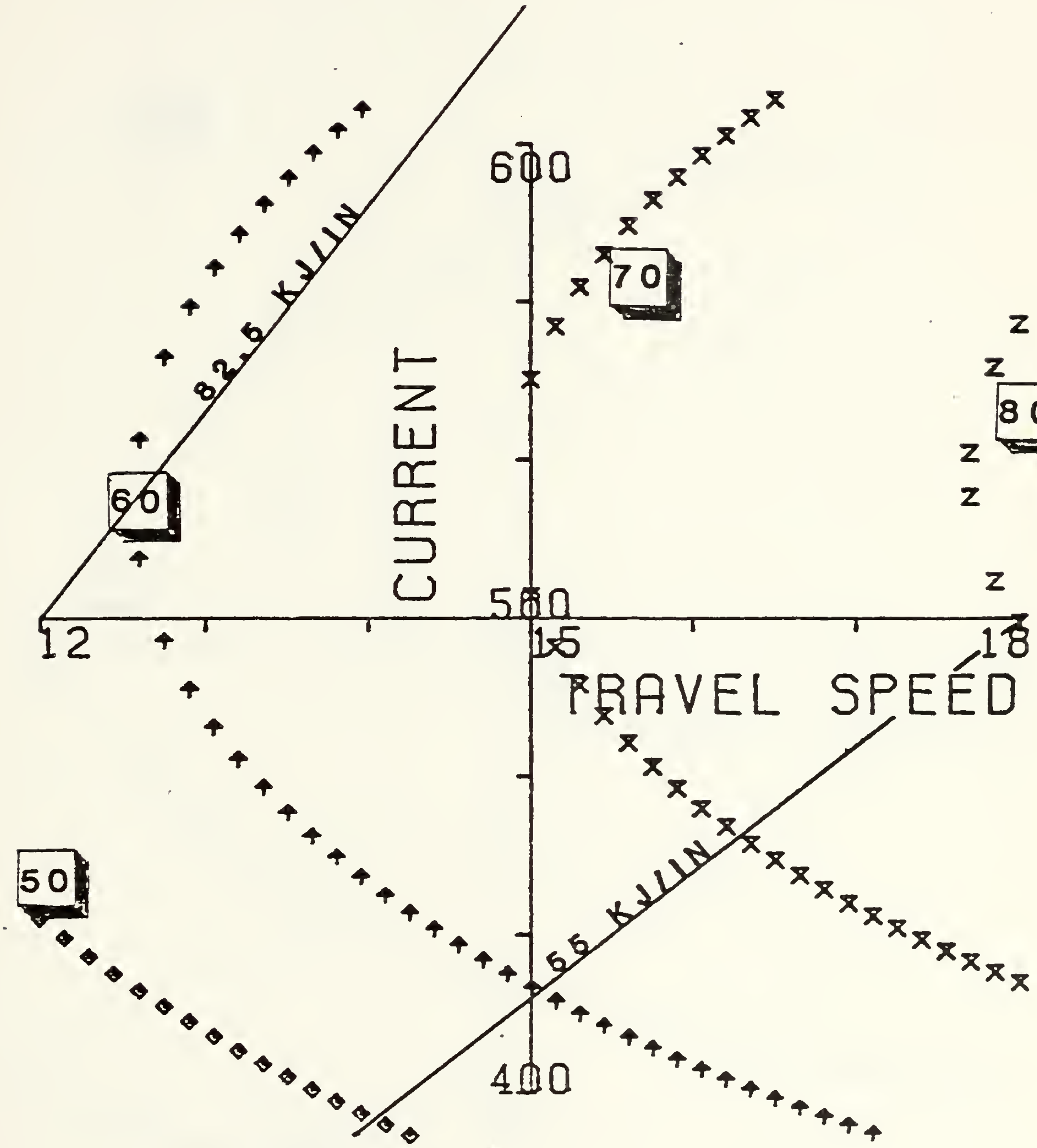


VOLTAGE 30

(FT-LBS)

ISO CHARPY ENERGY

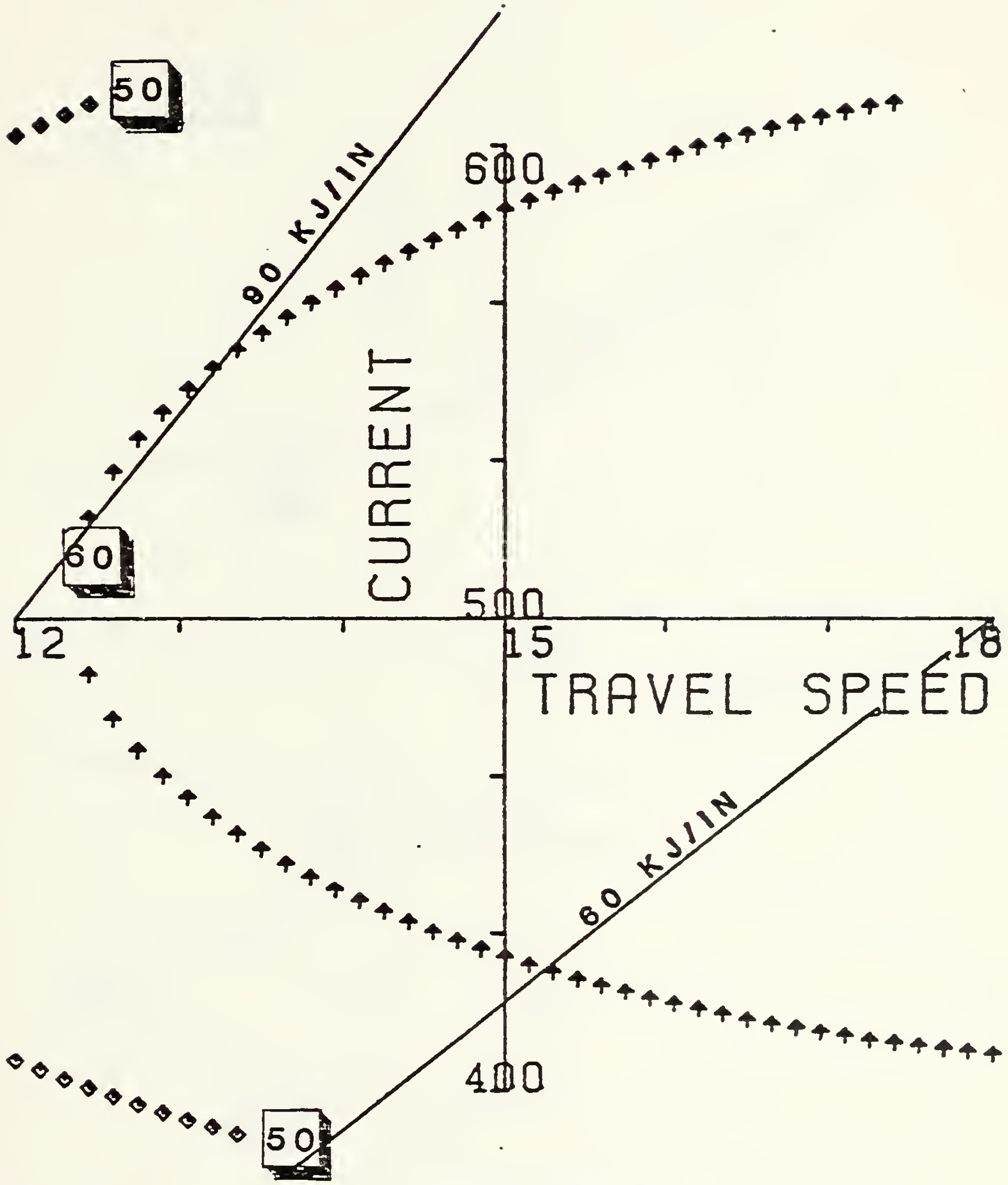
OP 121 TT



VOLTAGE 33
(FT-LBS)

ISO CHARPY ENERGY

OP 121 TT

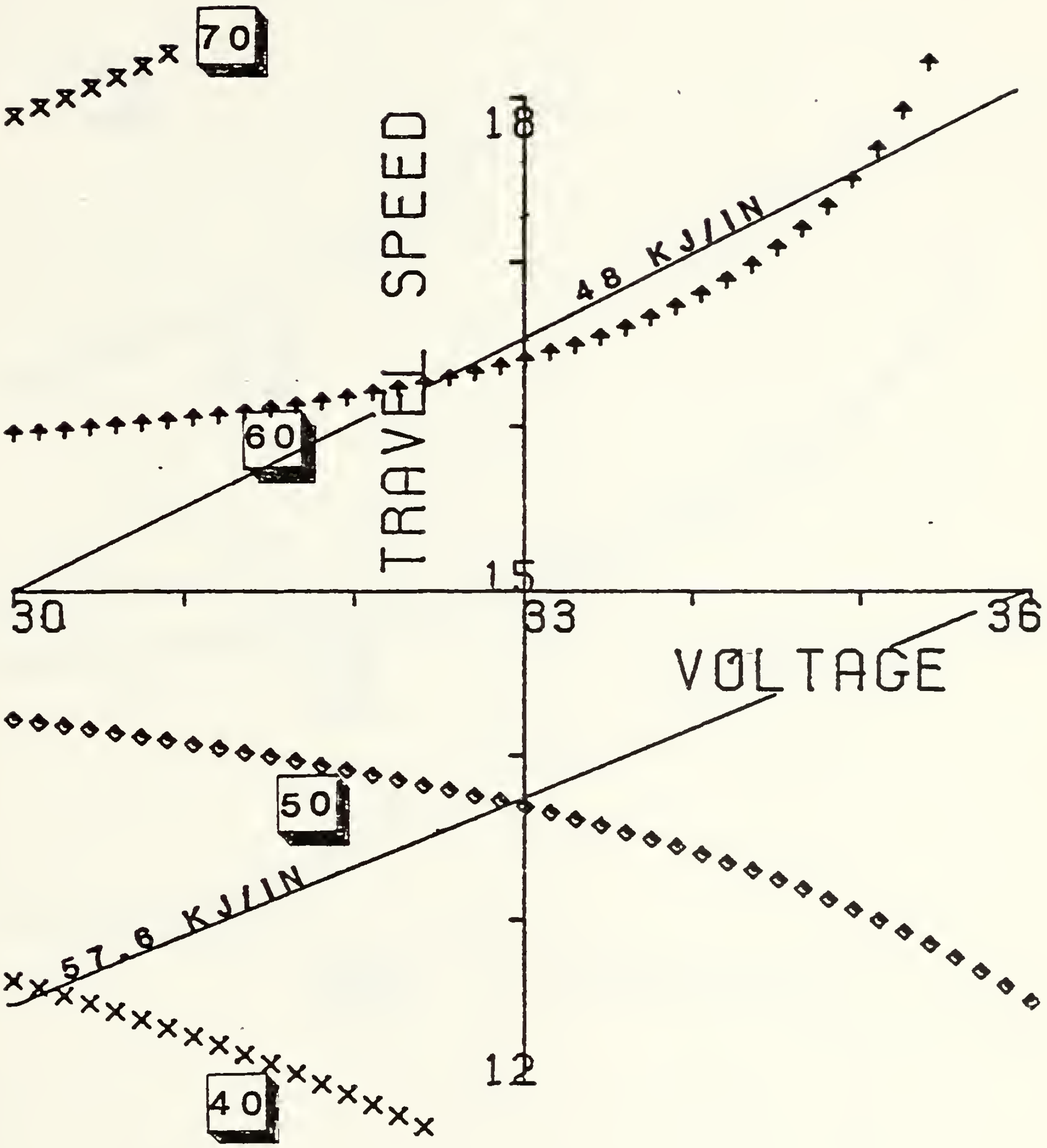


VOLTAGE 36

(FT-LBS)

ISO CHARPY ENERGY

OP 121 TT

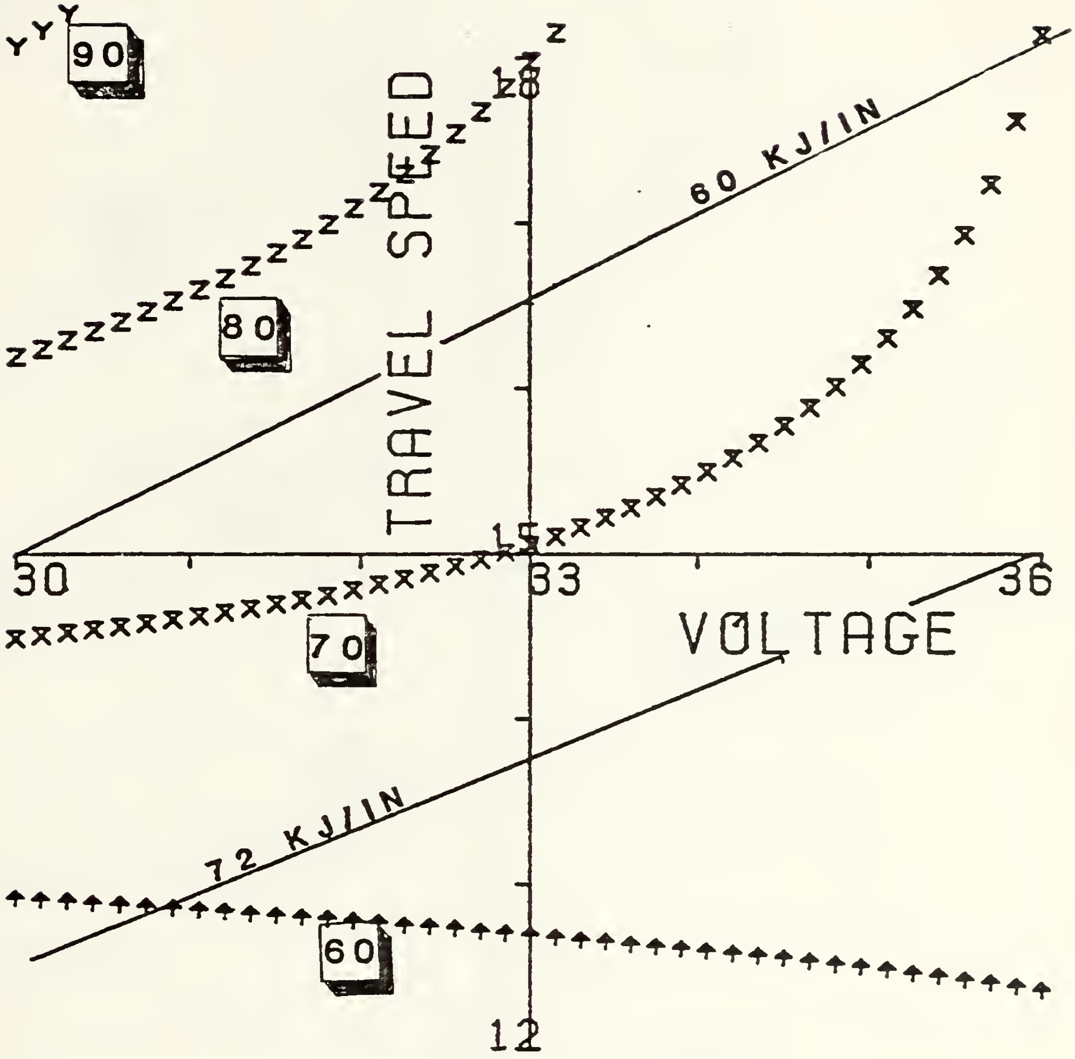


AMPS 400

(FT-LBS)

ISO CHARPY ENERGY

OP 121 TT

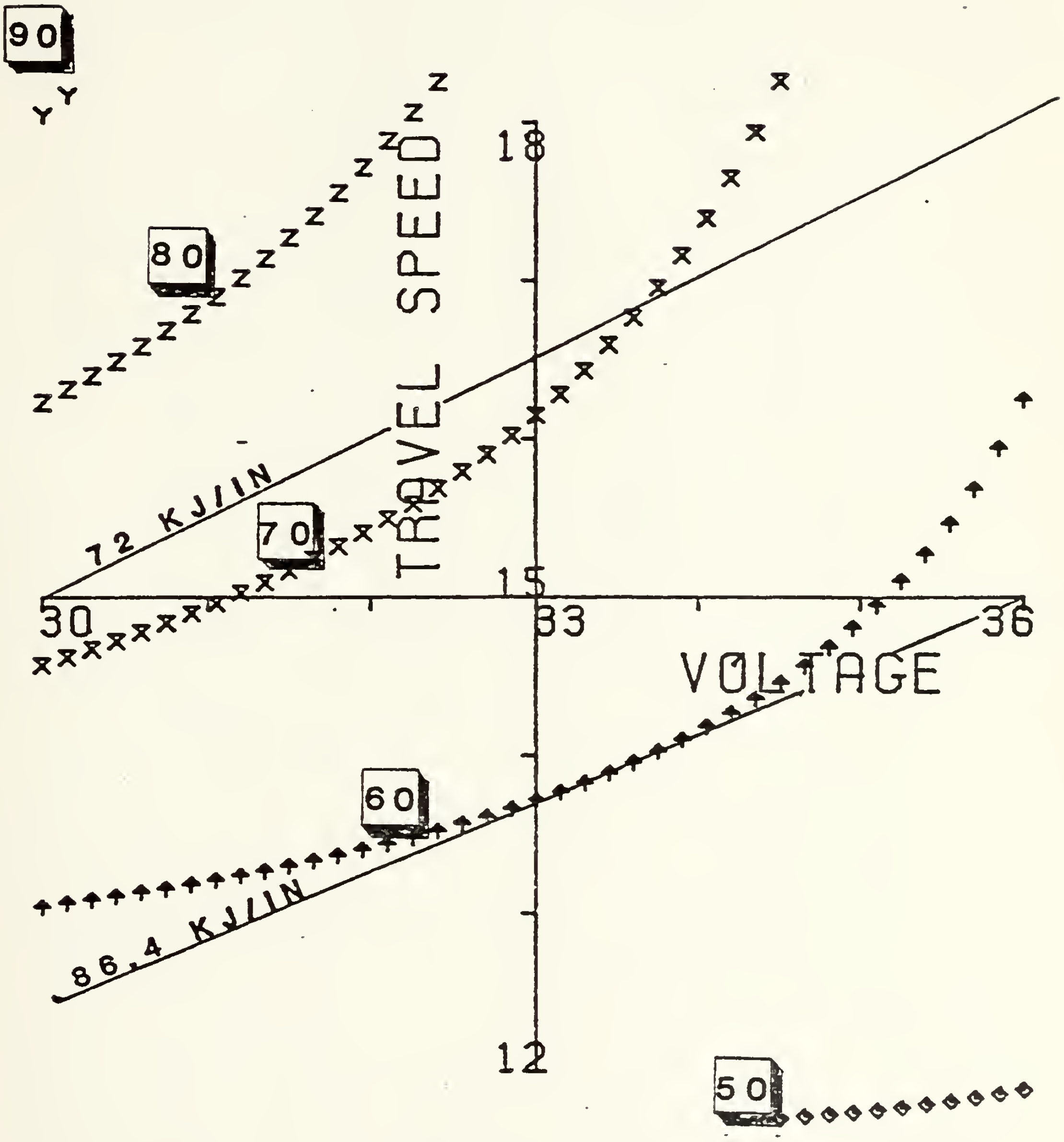


AMPS 500

(FT-LBS)

ISO CHARPY ENERGY

OP 121 TT



AMPS 600

(FT-LBS)

Thesis 199475
W63145 Wilson
c.1 Fracture toughness of
submerged arc welded
HY-80 steel.

Thesis 199475
W63145 Wilson
c.1 Fracture toughness of
submerged arc welded
HY-80 steel.

thesW63145
Fracture toughness of submerged arc weld
3 2768 001 90121 8
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